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Teaching of Design of Experiment to the First-Year Electrical Engineering Students

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Teaching of Design of Experiment to the First Year Electrical Engineering Students

***Abstract*:** In the traditional Electrical Engineering curriculum, courses are introduced and taught progressively from the most fundamental subjects, such as circuit theory, for example, to more advanced subjects such as power electronics and electric drives. To complement the teaching of concepts, laboratory components are used to augment the courses in order to enhance students' mastery of the subject matter and its applications. Usually, the capstone design course at the senior level allows students to synthesize what they learned and exercise their creative ability. The main goal is to facilitate an environment for students to walk through the entire design process from the formulation of ideas, through implementation, test and validation. There are many reasons that might contribute to the difficulty faced by the students in their ability to synthesize and be creative. Two specific contributing reasons that we identified and attempted to address are (1) insufficient critical thinking exercises and (2) lack of self-motivated activities unlike the cook-book style of laboratory exercises which, in general, is where students begin to learn the hands-on implementation of a design.

In this paper, we report on how the re-structure of the laboratory activities in Circuit I, a second-semester freshman-level course, help to introduce the concept and activities of "Design of Experiment". Instead of the traditional follow-the-steps experiments that students perform to understand the various aspects of the Circuit I concepts covered in the lecture class, students are required to first understand the circuit, the intended results, and only then expected to design the experiment (DOE) needed to validate the intended results. At the end, students are required to produce documentation of the testing procedure so that the DOE can be repeated by other students. This reverse process of learning requires students to be more proactive in identifying (1) the factors to be tested, (2) the levels of those factors, (3) the structure and layout of experimental runs and operating conditions. Students are therefore made more aware of how to deal with measurement errors, unexplained variations, and how to properly use the equipment in the laboratory. These three points are precisely the essence of the DOE. The challenge comes when the process above is introduced in the course because the students are being exposed, for the first time, not just to circuit theory but also to the laboratory equipment and how to conduct experiments in the laboratory. Assessment of the results will be presented and discussed as well. The main goal of the first year laboratory activities is not to focus on electric circuit design, but rather to emphasize the critical thinking needed to design the experiment and prepare the relevant documentation. In addition to instilling critical thinking early on in the curriculum, it also allows us to measure more specifically the "design" aspect of the particular ABET Student Outcome "ability to design and conduct experiment, as well as to analyze and interpret data".

I Introduction

The ECE department at Gannon University has attempted ways to incorporate Bloom's learning taxonomy in the design of the ECE curriculum and the delivery of classroom teaching and laboratory instruction with the emphasis on *knowledge* for freshmen-level courses, *comprehension* for sophomore-level courses, *application and analysis* for junior-level courses and eventually, *evaluation and creation* for senior-level courses [1]. In particular, the capstone design course at the senior level allows students to synthesize what they learned and exercise their creative ability. The main goal is to facilitate an environment for students to walk through the entire design process from the formulation of ideas, through implementation, test and validation. However, it has been consistently observed in the past that many seniors were having difficulty in gathering a test set together when it comes time to validate their designs. Most often, they struggled through a lengthy trial-and-error effort to get this done. More often than not, they were also reaching the end of the term and commented their wish to have more time for improvement. There are many reasons that might contribute to the difficulty faced by the students in their ability to synthesize and be creative. Two specific contributing reasons that we identified and attempted to address in this paper are (1) insufficient critical thinking exercises and (2) lack of self-motivated activities unlike the cook-book style of laboratory exercises which, in general, is where students begin to learn the hands-on implementation of a design.

To address these issues, we began the process of instilling the concept of *Design of Experiment* (DOE) early on in the curriculum. If proven successful in our implementation, the concept of DOE will be propagated throughout the curriculum with different levels of emphasis on the level of learning on the DOE. Generally speaking, DOE is a systematic method to determine the relationship between factors affecting a process and the output of that process. In other words, it is used to find cause-and-effect relationships. This information is needed to manage process inputs in order to optimize the output. Over the years, the benefits of DOE implementation in engineering and other science curricula have been reported [2-7]. In particular, it has been observed [2] that the lack of coherent learning objectives for laboratories has limited their effectiveness and hampered student retention of laboratory practices. In fact, at some American universities, DOE is offered as a fundamental course in programs such as Industrial and Systems Engineering [3]. In another instance, the DOE laboratory in the Mouse Factory [4] focuses on screening designs contained in two laboratory assignments. The first assignment establishes a benchmark of the current operational settings. The second assignment is to implement a fractional factorial experiment, develop a model, find an improved setting and compare the difference between the improved setting and the original setting (found in the first DOE laboratory assignment). Low-cost engineering experiments to reinforce the DOE method have been considered in traditional courses taught using the lecture format only [7].

In this paper, we report on how the re-structure of the laboratory activities in Circuit I, a second-semester freshman-level course, help to introduce the concept and activities of DOE. Instead of the traditional follow-the-steps experiments that students perform to understand various aspects of the Circuit I concepts covered in the lecture class, students are required to first understand the circuit, the intended results, and only then expected to design the experiment (DOE) needed to validate the intended results. In addition, what we are looking for at the end of the term is to have students produce documentation of the testing procedure. The documentation produced should be clear and self-contained enough for other students to be able to repeat the experiment as the judging criteria for scoring.

This reverse process of learning requires students to be more proactive in identifying (1) the factors to be tested, (2) the levels of those factors, (3) the structure and layout of experimental runs and operating conditions. Students are therefore made more aware of how to deal with measurement errors, unexplained variations, and how to properly use the equipment in the laboratory. These three points are precisely the essence of the DOE. The challenge comes when the process above is introduced in the course because the students are being exposed, for the first time, not just to circuit theory but also to the laboratory equipment and how to conduct experiments in the laboratory. Augmented with the requirements that we want students to gain the ability to write a reasonable good documentation as the final result, the decision has to be made as to the expectation and tradeoff on the aspects of DOE learning and the writing requirements.

In addition to instilling critical thinking early on in the curriculum, it also allows us to measure more specifically the "design" aspect of this particular ABET Student Outcome (SO) "*ability to design and conduct experiment, as well as to analyze and interpret data*". In the past, the "design" aspect of the SO is mostly measured and justified in the senior capstone design course. The assessment results from data collected at the mastery-level senior capstone design course will generate sets of action items as feedback to program for improvement. The process is particularly time effective if the assessed results at the end meet the expectations since, laterally you could justify meeting an outcome by investigating evidence from one course at mastery level. However, what if the assessed results indicate there are concerned areas that need to be improved. Without including courses at the introductory or reinforced level in the assessment and evaluation processes, critical information on the root causes for issues to arise at the mastery level cannot be captured. Hence, including DOE in the early curriculum for program evaluation will provide critical information and added advantage to the program evaluation process for measuring this specific SO. In this paper, we will first present the general structure of the Circuit I course, and then discuss where to introduce the DOE component. The details on the results of implementation and assessment are presented and discussed.

II Circuit I contents structure

Circuit Theory is covered in two semesters. Circuit I focuses on DC circuit theory and Circuit II on AC circuits. Circuit I is offered in fall as the second-semester freshmen-level course and Circuit II in spring as the first-semester sophomore-level course. Both are 4-credit courses that come with a three-hour laboratory component. The book by Alexander and Sadiku on *Fundamentals of Electric Circuits* [11] is adopted for these two courses. The contents of the course closely follow the chapters in the book. The following is the list of topics covered in Circuit I:

1. Basic concepts – concepts on current, voltage, power, etc.
2. Basic laws – Kirchhoff's laws, series/parallel circuits, delta-wye conversion, etc.
3. Methods of analysis – Nodal and Mesh analysis
4. Circuit theorems – superposition, Thevenin's and Norton's theorems, etc.
5. Operational amplifiers – ideal Op Amp, inverting, noninverting, summing, difference and cascaded Op Amp, etc.
6. Capacitors and Inductors – series/parallel capacitors/inductors, and their applications in Op Amp circuits, etc.
7. First-order circuits – source-free and step-response of RC and RL circuits and their applications, etc.
8. Second-order circuits – source-free and step-response of RLC circuits and their applications, etc.

The laboratory component of Circuit I covers the following exercises to complement the topics discussed in class:

Lab 1: Introduction to laboratory instruments
The first laboratory session is to allow students to become familiar with some of the equipment to be used in the laboratory as part of this course. Topics such as (1) Ohm-meter use for resistance measurement and understanding the tolerance values and color codes for resistors; (2) DC voltage and current measurement of resistor circuits; (3) effect of meters on DC circuits measurement. In addition, laboratory safety and report writing format are discussed.

Lab 2: Electrical component measurement and statistical analysis
The second laboratory session first focuses on the measurement of several resistors, capacitors, and inductors. The students must then perform a statistical analysis of each type of component for a given value. The concept of mean and standard deviation is introduced for the analysis of the laboratory results.

Lab 3: PSpice program
The concept, features, and usage of PSpice are introduced. Students learn to construct DC circuits using PSpice for DC analysis. The book by Marc E. Herniter on *Schematic Capture with Cadence PSpice* [12] is adopted for the lab class.

Lab 4: Kirchhoff's Law
This laboratory session is to verify Kirchhoff's voltage and current laws. Series and parallel circuits are assigned for construction and studies of the voltage and current laws. The concept of node and mesh analysis is verified as well. Students use PSpice to generate results for comparison with those measured in the laboratory.

Lab 5: Linearity and Superposition
This laboratory session aims to observe the principles of linearity and superposition in resistive networks. A single DC source cascade circuit is used to study linearity, whereas a cascade circuit with two DC sources is used to study superposition. Students calculate and measure voltages and currents and also compare results with those obtained by PSpice simulation.

Lab 6: Practical sources, Thevenin and Norton circuits
Students observe and study the properties of non-ideal sources, Thevenin, and Norton equivalent circuits in this laboratory session. The practical source will have an internal resistance. In order to measure this resistance, a variable resistor (potentiometer) is connected across the terminals of the source as a load. The power delivered to the load resistance can be varied by changing the value of the potentiometer. The ratio of voltage to current corresponding to the case of maximum power transfer is the internal resistance. Similarly, students need to compare results with those obtained from PSpice simulation.

Lab 7: Operational amplifier circuits
This laboratory session is allowing students to confirm the equation of some Op Amps circuits: inverting, summer, voltage followers, and non-inverting Op amps.

Lab 8: Use of oscilloscope
The eighth laboratory session focuses on how to perform measurements with a digital oscilloscope. Oscilloscope basics like vertical system controls, horizontal system controls, trigger controls, sin-wave measurement, amplitude measurement, and time measurement are covered.

Lab 9 and 10: PSpice Analysis of RLC circuits
This two week laboratory session is a project which focuses on using the transient analysis feature of PSpice on RLC circuits and comparing this with the results obtained by hand calculation in order to reinforce the concept covered in the Circuit I lecture class.

In the first laboratory session, the format of the formal laboratory report was discussed. Students are made aware that the following are, in general, the contents required in the formal report: (1) title page, (2) abstract, (3) acknowledgments, (4) table of contents, (5) list of tables, (6) list of figures, (7) objectives, (8) introduction/background, (9) theory, (10) experimental results and discussions, (11) experimental apparatus, (12) conclusions, (13) references, and (14) appendices. However, for Circuit I, the focus is on the format and basic writing. Hence, the students are only required to do items (1), (7), (8), (10), (11), (12) and (14).

Circuit I is a fast paced course. Contents need to be covered in time for the students to gain reinforcement of the concept in the laboratory sessions. There are three in-class examinations. Homework sets are assigned weekly except during the week when there is an in-class examination.

In order to implement the concept of DOE, students will need to be sufficiently prepared with the knowledge and experience not only to conduct and analyze experimental data, but also with the use of equipment in the laboratory as well as the knowledge of the circuits. Hence, logically, the place to inject the DOE exercises is after Lab 8 when students have sufficient exposure to basic circuit analysis and equipment usage. As a result, the original project on PSpice analysis of RLC circuits is further streamlined and scaled down to be part of the Circuit I lecture class assignment to make room for the DOE exercises. The following section will discuss the DOE exercises in details.

III DOE exercises

The DOE focuses on "design of experiment", not on "design of circuit". The design of circuit will go through a different process that includes brain storming of ideas, defining specifications, evaluating the options for design, implementation, test and validation. For Circuit I, students have not been exposed to the concept of any design processes for devices. It is also not the primary focus of this class. For our curriculum design, Circuit I focuses on *knowledge* in Bloom's learning taxonomy. Hence, the DOE introduced here is to reverse the process of performing a regular laboratory exercise. This reverse process of learning requires students to be more proactive in identifying (1) the factors to be tested, (2) the levels of those factors, (3) the structure and layout of experimental runs and operating conditions. Students are therefore made more aware of how to deal with measurement errors, unexplained variations, and how to properly use the equipment in the laboratory. These three points are precisely the essence of the

DOE [8-10].

There were initially two circuits to be considered for this DOE exercises. The first circuit is the *overload current detection* and the second circuit is the *digital-to-analog converter*. They are separately discussed next.

Overload current detection:
Figure 1 shows a proposed overload current detection circuit to be considered for the DOE.

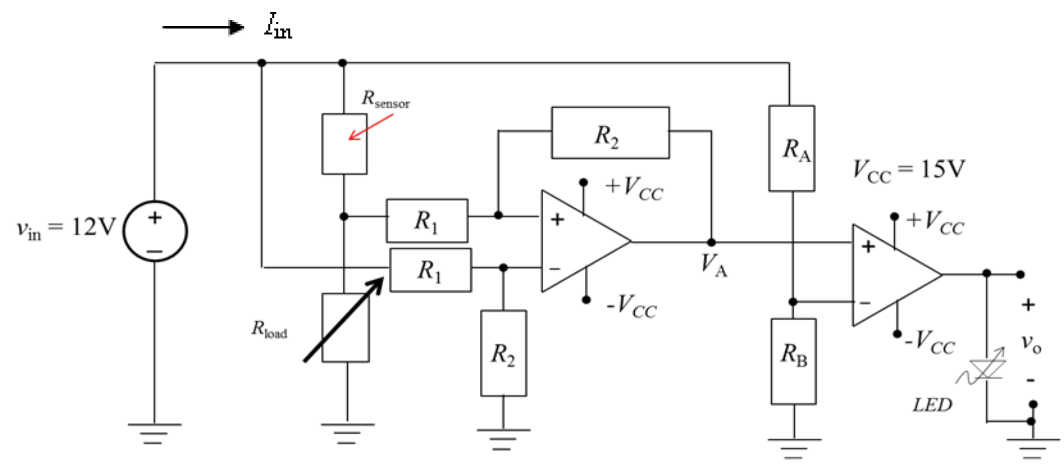

Figure 1: Overload current detection circuit for DOE consideration

Given design parameters:

v_{in} = 12 V; V_{trip} = 6 V; I_{trip} = 10 mA and P (max. consumption by load) = 60 mW.

The corresponding equations for circuit analysis are:

$$I_{in} = \frac{P_{max}}{v_{in}} = \frac{60 \text{ mW}}{12 \text{ V}} = 5 \text{ mA}$$

$$R_{sensor} = \frac{(0.005)P_{max}}{I_{in}^2} = \frac{\left(5\text{x}10^{-3}\right)60\text{x}10^{-3}}{25\text{x}10^{-6}} = 12\,\Omega$$

$$V_{sensor} = \left(I_{trip}\right)R_{sensor} = \left(2I_{in}\right)R_{sensor} = (10 \text{ mA})(12\,\Omega) = 0.12 \text{ V}$$

$$V_A = \left(\frac{R_2}{R_1}\right)V_{sensor} = V_{trip} = 6 \text{ V} \Rightarrow \left(\frac{R_2}{R_1}\right) = 50$$

$$V_{trip} = 6 \text{ V} = \left(\frac{R_B}{R_A + R_B}\right)v_{in} = \left(\frac{R_B}{R_A + R_B}\right)(12 \text{ V}) \Rightarrow \left(\frac{R_B}{R_A + R_B}\right) = \frac{1}{2}$$

and with

R_1	R_2	R_A	R_B	R_{load} (pot.)
1 kΩ	50 kΩ	10 kΩ	10 kΩ	0 - 5 kΩ

With this circuit [13], students can design an experiment to examine, for example, the following:

(1) if the design parameters were to change, what are the limiting factors to consider
(2) verify the results from calculated values

Digital-to-analog converter:
Figure 2 shows a digital-to-analog converter circuit to be considered for DOE.

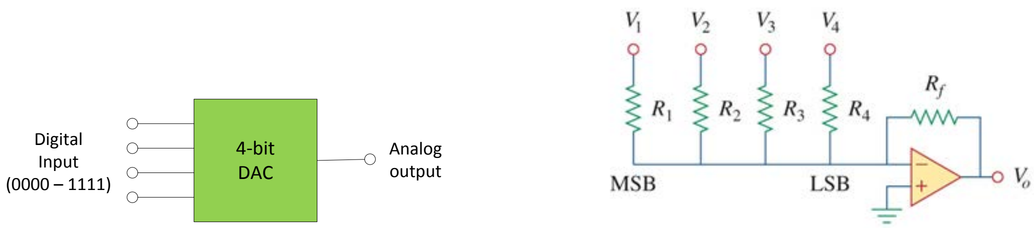

Figure 2: Digital-to-analog converter for DOE consideration

The four-bit DAC can be realized by a *binary weighted ladder*. The bits are weights according to the magnitude of their place value so that each lesser bit has half the weight of the next higher. The output and inputs relationship is given by the following equation:

$$-V_o = \frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3 + \frac{R_f}{R_4}V_4$$

Where $V_1$is called the *most significant bit* (MSB), while V_4 is the *least significant bit* (LSB). Each of the binary inputs can assume only two voltage levels: 0 or 1V. With this circuit, students can design an experiment to examine the following:

(1) verify the operation of digital-to-analog conversion
(2) construct source circuits to provide signals as digital inputs

We decided to go with the second circuit: digital-to-analog converter for the following reasons (1) the DAC circuit is an application example in the same textbook [12] used in the lecture class that has sufficient description of the background information for the circuit, (2) students need not spend excessive time to research the circuit just so as to understand what they must try to achieve, (3) students are taking Digital Logic Design in the same term with Circuit I, hence they have sufficient knowledge to understand the DAC action on their own. Besides, we wanted to make it a little "fun", not difficult for students to focus on the design of the experimental procedures.

IV Conducting DOE exercises

The DOE exercises are conducted in two laboratory sessions. In the first session, the DAC circuit, its reference, and specifications on the operations are given to students as follows:

Given parameters:

- $R_1 = 10\,k\Omega$, $R_2 = 20\,k\Omega$, $R_3 = 40\,k\Omega$, $R_4 = 80\,k\Omega$, $R_f = 10\,k\Omega$
- Use UA741 Op Amp
- Table 1 summarizes all the possible combinations of inputs and the corresponding digital-to-analog conversion.

Table1: Input and output values of the four-bit DAC

Binary Input $[V_1 V_2 V_3 V_4]$	**Decimal value**	**Output (volt)** $-V_0$
0000	0	0
0001	1	0.125
0010	2	0.25
0011	3	0.375
0100	4	0.5
0101	5	0.625
0110	6	0.75
0111	7	0.875
1000	8	1.0
1001	9	1.125
1010	10	1.25
1011	11	1.375
1100	12	1.5
1101	13	1.625
1110	14	1.75
1111	15	1.875

Students are tasked to study and understand the circuit operation. They are to construct the circuit in PSpice and simulate/verify each of the combinations in Table 1.

In the second session, students are tasked with the following:

1. Identify, in the laboratory, all the components and equipment that are needed to construct the circuit according to Figure 2. Since Figure 2 is only a top-level conceptual circuit. Students must figure out how to construct sources for digital 0 and 1.

2. Track a detailed list of the components and equipment used.
3. Construct the circuit and have the laboratory TA or the instructor double check before turning on the power to the circuit.
4. Measure and records all values that allow them to compare measured results with those in Table 1.
5. Analyze data and make conclusions related to the accuracy of their designed experiment.
6. Write a laboratory procedure that could allow any student to follow through what they did.

Since they have performed the PSpice simulation of the circuit, they know how the circuit works ahead of time. Even with that knowledge, they often struggle with how to create digital 0 and 1 V sources that can provide the 16 digital combinations. When there is error, they lack the systematic process of trouble-shooting the circuit. We observed that since they design and put the measurement tools together from scratch, they have vast interest to get the circuit to work. The self-started process in design and construction instills the critical thinking in them.

The end result of the DOE exercises is the write-up of the laboratory procedure. They are asked to follow the same format for the write-up that we provide for Lab 8, for example. Our standard lab write-up comprises the contents illustrated in Figure 3 as a guideline for the students.

Experiment #
Title of Experiment

1.1 Objectives
Briefly describe the objectives of the experiment

1.2 Background
Briefly describe the background information needed for readers to understand what is involved in the experiment

1.3 Procedure
Spell out detailed steps with proper section titles. Each section shall contain only targeted results to be achieved. Equipment, figures or tables shall be provided to clearly indicate how experiment should be constructed and conducted.

1.4 Study Questions
List the critical or targeted analysis needed to be performed on the experimental data

1.5 Equipment
List of equipment to be used in the experiment

1.6 Reference
List of references to make life a little easier for readers to find information needed

Figure 3: Lab write-up guideline

V Assessment of DOE implementation

All students completed their designs and tasks. We believe DOE introduced at the freshmen level is the right call to make. We have used EvalTools® [14], an online assessment tool, to conduct the survey on the following questions:

- Think more and be more aware of what the objectives of the circuit being built
- Understand better and be more familiar with the use and operation of the laboratory equipment
- Understand better the input constraints of the circuit
- Understand better the selection of the laboratory equipment/circuit components needed
- Think more critically of every step of the experiment

Figure 4 shows the results from EvalTools®:

Design of Experiment Experience

Compared to the traditional method of doing experiments, this Design of Experiment (DOE) allows me to:

	Questions	*Strongly Agree*	*Agree*	*Neutral*	*Disagree*	*Strongly Disagree*	*N.A.*	Mean(5)	**sd**
1	Think more and be more aware of what the objectives of the circuit being built	57.1	42.9	0.0	0.0	0.0	0.0	**4.6**	**0.35**
2	Understand better and be more familiar with the use and operation of the laboratory equipment	71.4	28.6	0.0	0.0	0.0	0.0	**4.7**	**0.29**
3	Understand better the input constraints of the circuit	71.4	28.6	0.0	0.0	0.0	0.0	**4.7**	**0.29**
4	Understand better the selection of the laboratory equipment/circuit components needed	100.0	0.0	0.0	0.0	0.0	0.0	**5.0**	**0.00**
5	Think more critically of every step of the experiment	71.4	14.3	14.3	0.0	0.0	0.0	**4.6**	**0.39**
	Total Class Response:	**74.3**	**22.9**	**2.9**	**0.0**	**0.0**	**0.0**	**4.7**	**0.26**

1 **Compared to the traditional method of doing experiment, what do you really like best of the DOE?**

- I liked the fact that I could make errors and had to fix them. I also enjoyed the fact that I got to design my own circuit and actually had to understand why each part was connected in such a way. I also think it made the lab report easier because one needs to analyze if it was done right, and which way was best.
- I like that I could work in my own way in order to get the result
- That it is what we create so we know exactly what to do
- It allows the student to approach the problem in a more creative way instead of just following the steps. It gives the student a better understanding of how the circuit works.
- I liked the critical thinking that is involved in creating your own experiment. The PSpice simulation lab really helped to create an understanding of the circuit that made the designing the physical circuit much easier.
- I think that I get hands on experience and become familiar with the tools

2 **Compared to the traditional method of doing experiment, what do you really dislike of the DOE?**

- I really did not dislike anything, but I will say that it would have been impossible to do the DOE if it involved the first experience with something like an oscilloscope and good directions on using the oscilloscope were lacking.
- I don't dislike anything. I just think it was a little bit harder because we have to figure out how to walk through every step.
- if you don't know how to get started it makes the experiment really hard
- It was challenging finding the correct equipment at times, either because other people were using all the cables or the lab simply did not have the equipment, mainly the correct resistors.
- I enjoy learning how to use the equipment

Figure 4: Survey results for DOE implementation

In Figure 4, the students' comments were also captured. The comments and the survey results are consistent with what we observed and concluded. To re-iterate, students are more aware of what they were trying to build, and paid greater attention to input constraints and the usage of relevant equipment. More importantly, they are more critical of every step of the experiment. A sample of the laboratory write-up on the DOE submitted by one student is given in the Appendix. In conclusion, a simple and straight forward way to implement DOE exercises in the freshmen level course titled Circuit I is the right approach to instill critical thinking for hands-on experience. In addition, it is the right place, based on student aptitude and attitude, to work on their own engineering circuit design process. With this success, we plan to implement DOE exercises with different levels of emphasis in advanced courses as well.

V Conclusions

In this paper, a novel approach is presented to demonstrate how a simple and straightforward way of reversing a laboratory exercise to focus on *Design of Experiment* instead of following the cook-book style of conducting the experiment, collecting and analyzing the data, can instill essential critical thinking skills in the students. We observed that by implementing DOE at the right juncture in the sequence of laboratory exercises for the course, not only allowed students to be critical thinkers of their work, but also enhanced their interest in the subject matter. For the freshmen level of DOE implementation, the key is to make the experiment relevant to what they have while gaining sufficient knowledge and having "fun". The emphasis was on "design of experiment", not on "design of circuit".

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APPENDIX: Sample Student's DOE report

EXPERIMENT 10

DESIGN A DAC CIRCUIT

10.1 Objectives

The purpose of this lab is to understand, create, and test the operation of a Digital-to-Analog converter circuit.

10.2 Background

A four-bit DAC consists of four separate voltage sources that individually connect to a resistor. These voltage sources then connect to the negative terminal of the uA 741 operational amplifier. The positive terminal is connected to ground. Another resistor is connected from the negative terminal to the output terminal. The voltage source that is furthest from the operational amplifier represents the most significant bit, the voltage source that is closets to the operational amplifier represents the east significant bit. Each voltage source can only assume two voltage levels: 0V or 1V. The equation that relates the output voltage to the input voltage is

$$-V_o = \frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3 + \frac{R_f}{R_4}V_4$$

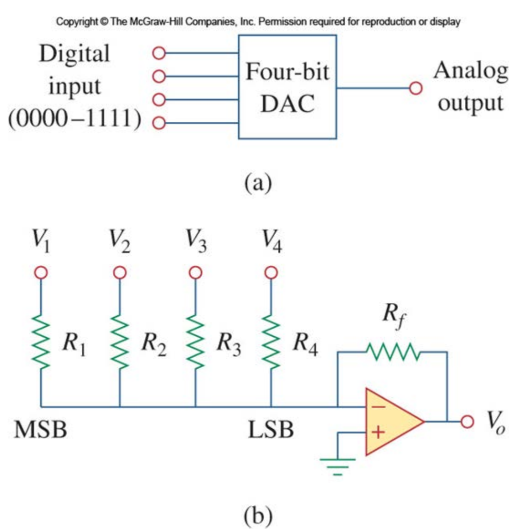

Figure 1: 4-bit DAC

10.3 Procedure

1. Setup the power source up by connecting the negative terminal to the positive terminal, this terminal becomes the ground. Connect the ground from the DC power supply to the ground on the op amp. Plug the positive terminal from the power supply to the positive terminal of the op amp. Plug the negative terminal from the power supply to the negative terminal of the op amp.
2. Connect the four resistors, R1-R4, in parallel.
3. Setup a potentiometer by connecting one terminal to the negative terminal of the op amp, one terminal to the ground on the op amp, and one terminal to R1, the first resistor. This potentiometer will control the voltage that R1 receives. To measure the voltage, connect a multimeter to each potentiometer from the ground terminal of the potentiometer to the terminal of the potentiometer that is connected to the resistor.
4. To setup the potentiometers for the remaining three resistors, repeat the above procedure three times.
5. Connect Rf from the negative op amp terminal to the output terminal of the op amp.
6. Connect a multimeter in series from the ground terminal of the op amp tot the output terminal of the op amp.
7. Using the multimeters, set all potentiometers to 0V. Record V_o.
8. Set the potentiometer connected to R4 equal to 1V. Record $V_{o.}$
9. Continue in this manner for all remaining binary numbers on the table. Record $V_{o.}$

Table1: Input and output values of the four-bit DAC

Binary Input $[V_1V_2V_3V_4]$	**Decimal value**	**Output** $-V_0$
0000	0	0
0001	1	0.125
0010	2	0.25
0011	3	0.375
0100	4	0.5
0101	5	0.625

0110	6	0.75
0111	7	0.875
1000	8	1.0
1001	9	1.125
1010	10	1.25
1011	11	1.375
1100	12	1.5
1101	13	1.625
1110	14	1.75
1111	15	1.875

10.4 Study Questions

1. Verify the results of the lab using PSpice
2. Validate your results by finding the percent error

10.5 Equipment

1. DC Power Supply
2. 5 Multimeters
3. 5 Resistors
    a. R1 = 10 kΩ
    b. R2 = 20 kΩ
    c. R3 = 40 kΩ
    d. R4 = 80 kΩ
    e. Rf = 10 kΩ
4. Analog module
5. 4 50 kΩ potentiometers
6. Plug board