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Lab in a Box: Redesigning an Electrical Circuits Course by Utilizing Pedagogies of Engagement*

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A lecture-based theoretical approach is frequently utilized when teaching courses in electrical circuits and the educational learning objectives are often limited solely to content learning. This paper describes how a lecture-based electrical circuits' course was redesigned utilizing pedagogies of engagement to produce an environment that stimulates creativity and allows for the following additional learning objectives to be pursued: (1) improvement of hands-on skills, (2) increase in design abilities, and (3) teaming/collaboration proficiency. Educators are often deterred from pursuing these additional learning objectives in a large classroom or when there is lack of space and equipment. In this study, a "lab in a box" approach is outlined and shown to overcome these deterrents and foster an environment of student engagement. An inexpensive and easy-to-maintain portable kit was developed to enable approximately 300 undergraduate students each year to build and design electrical circuits. While teaching a course titled *ENGR 2431–DC Circuits* for years in a traditional large lecture-based classroom, the instructor was eager to adopt an alternative pedagogy to increase students' intrinsic motivation and overall engagement in the class. The expected benefits of the project in the near term were to increase student engagement and add three additional learning objectives to the course. After implementing the "lab in a box" project in a large classroom, survey data and observational experiences provided an indication that students are more engaged and in control of their learning.

Keywords: engineering education; electrical circuits; pedagogies of engagement; hands-on in a large classroom; project-based learning; object interaction

1. Introduction

A lecture-based approach is often utilized by instructors teaching undergraduate engineering courses in electrical circuits. Electrical and Computer Engineering (ECE) students frequently have an accompanying laboratory or project-based experience to provide hands-on application of the electrical circuits' theory. Many schools also have students that are majoring in disciplines other than ECE that take one or more courses in electrical circuits. Those students are often referred to as "non-majors" because the topics covered are not a primary emphasis in their discipline. Non-majors are less likely to have a laboratory experience that goes along with their course in electrical circuits. Intuitively, it is much more beneficial for non-majors to learn about practical applications and get hands-on experience with circuits rather than only learning about the theory, especially since the ECE topics are outside their core area of study. Furthermore, ECE topics are often difficult to comprehend without application illustrations. References [1–3] show a few examples of how including practical hands-on applications have shown to be effective in teaching ECE topics. Educators are often reluctant to pursue hands-on engagement, particularly in a large classroom or when there is a lack of space or budget for equipment [4–6]. In an effort to provide hands-on learning that is more affordable and accessible, many institutions are turning to virtual, remote, or on-line laboratories [7–9]. These e-learning alternatives to physical labs often use software simulations instead of actual measurement tools. While there are logistical and financial benefits of discontinuing physical labs, offering a combination of both virtual and physical labs can be advantageous [10]. This paper builds on findings from our past work [11] and extends that study to describe the utilization of virtual simulation tools and an affordable "lab in a box" approach to demonstrate effective teaching of an electrical circuits course for non-ECE engineering majors. Furthermore, we applied pedagogies of engagement to enhance and encourage students' design and creative reasoning, hands-on skills, collaboration, and teamwork [12].

2. Background

In general, teaching electrical circuits' courses with a lecture-based approach can lead to many negative

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outcomes. Scholars suggest that these outcomes are: development of passive learning habits, reduced autonomy, lack of motivation, neglected communication skills, and fewer opportunities for learning and creativity [13, 14]. Recently, many engineering educators have used hands-on learning approaches to help students understand complex concepts and to experience object-interaction phenomena. A growing body of research provides evidence of the benefits of using inductive teaching methods, where learning outcomes are obtained through experimentation or simulation instead of only applying theory and equations in a deductive fashion [15]. It is encouraging that some educators are no longer relying purely on lecturing about high-level abstract concepts, but are utilizing student-centered active learning activities that provide a better understanding and object interaction of the concepts they learn. In several studies, active learning has shown to be an effective method to teach circuits concepts and to improve the quality of teaching and learning circuit design in various electrical engineering courses. These studies show that students engaged in active-learning environments claim to be more motivated and satisfied with what they are learning [13, 16–22].

One form of active learning is project-based learning (PBL). Scholarly work done by J.W. Tomas concludes that research on PBL implementation is largely limited to research on project-based science administered by teachers with limited prior experience with PBL [23]. The author points out that there is evidence that PBL is relatively challenging to plan and enact. J.W. Tomas also shows that there is some evidence that students have difficulties benefiting from self-directed situations, especially in complex projects. Some of these difficulties are associated with "initiating inquiry, directing investigations, managing time, and using technology productively" [23, pg. 36]. The author also suggests that effectiveness of PBL as an instructional method may depend on the incorporation of a range of supports to help teach students how to learn. Furthermore, this work reports that students and teachers believe that PBL is beneficial and effective as an instructional method as it "enhances professionalism and collaboration on the part of teachers and increased attendance, self-reliance, and improved attitudes towards learning on the part of students" [23, pg. 37].

In this study, pedagogies of engagement are applied through the implementation of the PBL approach. The study was performed at an institution that has a unique structure of its circuits' courses for non-majors. Instead of having one traditional semester-long course, three separate one-credit-hour courses are taught in a sequence. The work in this study focuses on the first course (titled *ENGR 2431 – DC Circuits*) that is taught in the first 6 weeks of the semester. Details about the two subsequent courses are described in [24]. An open source textbook was created for ENGR 2431 that contains a complete list of topics that are taught in the course [25]. It is important to note that while the instructor of *ENGR 2431* has an extensive experience in teaching laboratory courses and implementing projects in a variety of engineering courses, the project described in this paper is designed in such a way that it could be easily implemented by an instructor without vast experience in using pedagogies of engagement.

3. Learning objectives and project overview

A lecture-based theoretical approach is frequently utilized when teaching courses in electrical circuits and the educational learning objectives are often limited solely to content learning. This was the case for ENGR 2431 prior to the fall 2015 semester. This paper describes how ENGR 2431 (a lecture-based electrical circuits' course with enrollments that average well over 100 students) was redesigned utilizing pedagogies of engagement. The course redesign produced an environment that stimulated creativity and allowed for the following additional learning objectives to be pursued: (1) improvement of hands-on skills, (2) increase in design abilities, and (3) teaming/collaboration proficiency. Not only are these three additional learning objectives added with this course redesign, but the amount of content that is taught is also expanded to include many practical topics (e.g., how various sensors work and how to make measurements with a multimeter). The project in ENGR 2431 is appropriately called "project infinity" because many students will quickly forget how to perform difficult circuit theory calculations, but the hands-on skills needed to design/build circuits on a breadboard and make measurements with a multimeter are skills that should last much longer.

Project Infinity was introduced at the end of the first ENGR 2431 lecture. Two-person groups were formed and a project kit was checked out to each group. Students had the opportunity to self-select their group partner and were encouraged to have a partner selected prior to coming to the first class. Each of the groups were also encouraged to find another group and form an alliance with them so that they can have additional support and can share items in the kit if something breaks or a part is lost. Initially, the project was implemented to strictly follow the four-person alliance structure and even had "alliance challenge" exercises at the end of each of the three parts of the project to further force the reliance on the alliance structure. In these challenges, the two subgroups competed against each other to see who could design and build a circuit more efficiently. While formally using the alliance structure model was an effective way for the subgroups to interact more closely and test themselves, it was discontinued due to the short timeline of the six-week ENGR 2431 course and the difficulty the students had with scheduling four-person meetings outside of class to finish what was not completed during class time. The assessment of how effectively the students perform in their groups was accomplished with peer reviews that were completed after each part of the project was turned in, and again in the final survey that was submitted after the project was over.

For the project to be feasible for more than 100 students in a class taught in a large lecture hall, we developed an inexpensive and portable lab kit. The total price when ordering quantities of 100 units was around \$15 per kit. The 36 electrical components in the kit and other items fit comfortably in the plastic case (see Appendix I, Fig. 1). A resistor color code chart, which comes with the mpja.com breadboard, is affixed to the case to allow the students to quickly identify their resistors. Two 4.5 V AA battery holders (i.e. three AA batteries in series) are in the kit so that two supply voltage options are available for the circuit designs ($\sim$ 4.8 V and $\sim$ 9.6 V with new batteries). Alligator clips are used to allow a hands-free method to make measurements with the multimeter and provide a method to prevent the fragile meter leads from breaking. In the Fall 2015 semester, Project Infinity was implemented in an outdated classroom that had over 100 individual desks with fixed table tops and the students had no issues working with the lab kit in that non-ideal class setting. The project not only involves designing, building, and performing calculations, but also includes simulating the circuits using a SPICE-based program called Multisim [26]. Using Multisim was found to be an important aspect of the project because it gave the students experience in creating schematics and enabled them to check the correctness of their circuit measurements and their calculations. The students submit project deliverables using an Excel template that was uniquely designed by the instructor to make the project straightforward to complete, while also very efficient for grading. The template provides a novel way for the students to display their calculations, measurements, photos, Multisim screenshots, and comments. Another feature of the template is that the errors between the simulations, measurements, and calculations are prominently displayed to alert the students of potential mistakes and also to provide a useful tool when grading.

4. Project infinity description

We created the project to be in three parts with each part designed to take approximately two weeks for completion. The length of each part was designed to work with the time restrictions of the one-credit hour ENGR 2431 course taught over six weeks, which includes 13.3 total hours of class time. The first part of the project involved basic resistor-based circuits. Most of the sensors (e.g., Cadmium Sulfide cells, phototransistors, and thermistors) in the kit were also introduced in part 1 of the project. The second part involved advanced topics in resistor-based circuits and had more of a design focus. The third part introduced capacitors and inductors in RLC circuits. The following three learning objectives, described at the beginning of Section 3, were covered in each part of the project as follow:

1. **Design/creativity:** Many exercises required the selection of circuit types and resistor values to meet specifications.
2. **Hands-on skills:** The exercises involved the use of breadboards, multimeters, and required a significant amount of wiring.
3. **Teaming/collaboration:** The students worked with a partner and alliance members to complete the exercises.

The fourth goal—content learning—was specific to each of the three parts of the project. The following bullets show the primary topics that are covered in ENGR 2431 (topics below in *italic font* were added as a result of the course redesign that implemented Project Infinity and were not included in the course beforehand):

- Part 1: Kirchhoff's Voltage Law (KVL), Kirchhoff's Current Law (KCL), combining resistors in series and in parallel, and basic circuit equations such as Ohm's Law. Topics added in part 1: *Bread boarding, multimeters, Multisim, resistor color codes, sensors, diodes, and potentiometers.*
- Part 2: Mesh and Nodal Matrix Analysis, source transformation, superposition, Thevenin and Norton equivalent circuits, and the maximum power transfer theorem. Topics added in part 2: *Complex simulations and How thermistors can be used to trigger a transistor to turn a light emitting diode (LED) on and off. Transistors are also shown to provide the students with an example of a better way to turn on an LED.*
- Part 3: Combining capacitors or inductors in series and in parallel, RL and RC filter circuits, charging/discharging inductors and capacitors, DC steady-state analysis of RLC circuits, and equations involving capacitors and inductors. Topics added in part 3: *The concept of filtering*

is applied by the students in a hands-on fashion as they build low pass and high pass filters that pass or block the DC input, respectively.

5. Results

Survey data in Table 1 and exam data in Table 2 were used to evaluate the project and are discussed in sections 5.1 and 5.2. The survey statements allowed the students to evaluate the project. The questions were adapted from previous work where students participated in a study that employed PBL as a pedagogy of engagement [26].

5.1 Survey results

Survey statements 6 and 8 were not expected to improve as a result of the project, but were only included to provide an indication of how conscientious the students were when they took the survey. Survey statements 2 and 10 show that the students thought the project was difficult and time-consuming. These results would likely negatively affect the survey responses as a whole, however they support findings from previous research on PBL [23].

Three of the course learning objectives were mapped to survey statements 3, 4, and 5 in Table 1. Since well over half of the students agreed with these statements, it can be concluded that the students felt these learning objectives were achieved, but at different levels. For example, the hands-on skills learning objective was by far the highest scoring survey result with 87.9% agreeing with the statement: "The project strengthened my hands-on skills."

- Content learning: Item 3, score = 3.96, 77.1% agreed.
- Hands-on skills: Item 4, score = 4.33, 87.9% agreed.
- Design/creativity: Item 5, score = 3.73, 61.2% agreed.

The teaming/collaboration goal was not addressed directly in the survey, but since the students were working in teams throughout the project it is a logical assertion that their teaming/collaboration skills improved to some degree as a result of the project.

One of the previously mentioned challenges of ENGR 2431 is that there was a lack of student engagement prior to the course redesign. Survey statement 9 ("The project was interesting") was used as an indicator for student disengagement; the scores reported are high enough (score = 3.81, 70.3% agreed) that the project design appeared to provide some level of engagement to the students. Students also answered favorably (score = 3.55, 59.6% agreed) to survey statement 7—"The project made me more confident in my ability to apply course concepts to aspects of everyday life."

In Fall 2016 and Spring 2016 (two of the three cohorts in Table 1), the students were also asked if "the project should be done again in the next semester." They were given a yes or no field to answer and an area to clarify their answer. 226 of the students that agreed to participate in the study responded clearly to the question about whether or not to do the project again in the next semester; 201 out of the 226 (88.9%) students responded favorably. Furthermore, 18 out of the 25 students that did not think the project should be done again stated that the project's time requirement was the reason they responded negatively. As previously noted, the goal of the project was not to give the students an easy project that would take very little time to complete, but to add new content and learning objectives to the course.

5.2 Exam results

In order to assess the content learning goal, a controlled study was performed from the spring

Table 1. Survey Results (1 = Strongly disagree, 2 = Disagree, 3 = Neutral, 4 = Agree, 5 = Strongly Agree). Note: Avg = Average score, % 4 or 5 = Percentage of students responding positively (4 or 5 on a 5-point scale)

	Total (N = 321)		Fall 15 (N = 91)		SP 16 (N = 151)		Fall 16 (N = 79)	
Survey Statement	**Avg**	**% 4 or 5**	**Avg**	**% 4 or 5**	**Avg**	**% 4 or 5**	**Avg**	**% 4 or 5**
(1) The project was enjoyable.	3.48	**55.8%**	3.59	**60.2%**	3.46	**53.0%**	3.40	**56.3%**
(2) The project took too much time.	3.85	**70.5%**	3.67	**65.9%**	3.93	**74.8%**	3.90	**67.5%**
(3) The project contributed to learning of material.	3.96	**77.1%**	3.95	**73.9%**	3.89	**76.8%**	4.10	**81.3%**
(4) The project strengthened my hands-on skills.	4.33	**87.9%**	4.53	**96.6%**	4.25	**83.4%**	4.25	**86.3%**
(5) The project strengthened my design skills.	3.73	**61.2%**	4.01	**72.7%**	3.55	**53.0%**	3.75	**63.8%**
(6) The project increased my ability to communicate effectively.	3.43	**48.0%**	3.48	**46.6%**	3.50	**54.3%**	3.23	**37.5%**
(7) More confident in my ability to apply course concepts.	3.55	**59.6%**	3.67	**63.6%**	3.52	**58.9%**	3.49	**56.3%**
(8) I have a better understanding of professional responsibility.	3.24	**41.5%**	3.26	**43.7%**	3.25	**40.4%**	3.20	**41.3%**
(9) The project was interesting.	3.81	**70.3%**	3.90	**72.7%**	3.84	**72.8%**	3.64	**62.5%**
(10) The project was difficult.	3.76	**67.8%**	3.86	**73.9%**	3.71	**66.9%**	3.73	**62.5%**
(11) The project increased my interest in Engineering.	3.37	**47.0%**	3.33	**42.0%**	3.48	**53.0%**	3.21	**41.3%**

Table 2. Final Exam Score Results (p-values calculated using a two-tailed, unequal variance type T-Test)

Cohort	N	Exam Average	Exam Std. Dev.	p-value compared to SP15	Assessment Methods
SP15	179	79.7%	15.9%	1.0	Homework & Quizzes
FA15	98	70.2%	18.0%	0.000076	Project, **No Quizzes**
SP16	160	80.9%	14.5%	0.32	Project & Quizzes

2015 semester though the spring 2016 semester. The methodology and details of the study are explained below for each of the three semesters involved in this study. The analyses of the exam scores are shown in Table 2.

- **Spring 2015**: This was the last semester prior to the project being added. In an effort to force the students to keep up with the material, in-class preparation quizzes were frequently given during the course. The students were also assigned traditional theoretical homework assignments to be solved individually. 179 students took the course and the type of engineering majors' breakdown was: 101 (56%) Mechanical, 37 (21%) Chemical, 20 (11%) Industrial, 20 (11%) Civil, and 1 (<1%) Architectural.
- **Fall 2015**: 98 students took part in the study in the first semester the project was incorporated into ENGR 2431. The project replaced the homework assignments that were used in Spring 2015. Since it was the first semester that the project was included and the amount of class time needed to work on the project was difficult to predict, a decision was made to **not** have preparation quizzes that semester. The students were given plenty of time to work on the project in class, but a lot of them ended up choosing to do the project outside of class and left class early. Thus, the level of autonomy given to the students was determined to be too high and if all of the students didn't choose to use class time for project work then it would be better to keep the in-class preparation quizzes. 98 students took the course in the fall 2015 semester and they were a mixture of the previously described majors.
- **Spring 2016**: Improvements were made to the project after reviewing all of the data from the Fall 2015 cohort and in-class preparation quizzes were brought back, but they included questions over both the theory and the project. 160 students took the course and they were a mixture of the previously described majors (Mechanical, Chemical, Industrial, Civil, and Architectural).

The exam grades for these three cohorts are shown in Table 2. The exam contained 20 multiple choice questions over the standard topics that are traditionally covered in the class. The topics are shown in non-italicized font in the three bullets at the beginning of Section 4. The final exam scores were lower for the Fall 2015 cohort (70.2%) as compared to the Spring 2015 cohort (79.7%). This statistically significant 9.5% drop in exam scores is attributed to the removal of the preparation quizzes and also a result of the curricular design of the project being somewhat of a work in progress. After reintroducing the quizzes and making improvements to the project, the exam scores for Spring 2016 rose to 80.9%, which exceeded the average of Fall 2015 by 1.2%. The p-value was calculated to be 0.32 using a two-tailed, unequal variance type t-test. Using a significance level of $\alpha = 0.05$ this increase in exam score between the Spring 2015 and Spring 2016 cohorts is not statistically significant. While this result showed that the project didn't produce exam score increases that were statistically significant, it is important to note that the planned benefits of the project were to increase student engagement and facilitate including more practical topics in this non-majors course and also to implement additional learning objectives. A slight increase in the exam scores was a welcomed result, but a statistically significant increase was not expected to occur until much later after the project went through multiple rounds of refinements as each question representing the different topics in the course are analyzed and the project modified to better address each topic.

One of the lessons learned from this data is that the assessment of the theoretical topics in the course cannot be de-emphasized and preparation quizzes are an effective mechanism to accomplish this assessment. Results also show that replacing the individual theoretical homework with the project did not negatively affect the exam scores, and the content learning objectives did not suffer as a result of this PBL course design. Each of the 20 questions was also statistically analyzed to highlight theoretical topics where the project is deficient in covering the material. Using this feedback, the project can be continuously improved to add better practical applications and blend more theoretical questions into specific areas of the project to increase content learning. This method of continually refining the project should be maintained in order to keep improving the course each semester.

6. Conclusions

In an effort to promote pedagogies of engagement, this paper provides a blueprint for introducing a cost-effective project that can be completed inside or outside of the classroom. One of the largest benefits of this study is that it shows a realistic way to implement hands-on laboratory type work into a large lecture-based classroom. It also shows how practical topics and skills can be introduced into a theory-based electrical circuits' course for non-majors. To provide assistance for educators that desire to implement Project Infinity in their course, many of the details of the project are shown in Appendix I. Since the completion of this study, an Open Source textbook titled "*DC Circuits*" was written and introduced into ENGR 2431 to provide educational materials that are custom-built for the topics in the course. The book is under Creative Common (CC) license making it easy and free access to provide aids and tutorials to help students with the project.

The amount of content learned in the course was expanded due to the numerous additional topics that were introduced as a result of the project. The expansion in topics taught in the course is one of the most innovative parts of the course design. By introducing topics, such as sensors, diodes, and switches, early in the course it was easier for students to more fully understand them when they needed to use them for later parts of the project and also in other courses that follow ENGR 2431. Furthermore, exam scores were slightly improved when the project was added to ENGR 2431 in Spring 2016 when compared to the scores in Spring 2015 when there was no project. Further studies are needed to explore how similar pedagogy such as PBL can affect student performance on the final exam in different settings, such as a standard four-month semester long course instead of a compressed six-week course.

While our paper describes how the "lab in a box" project was effectively implemented into an electrical circuits' course taken by non-majors, parts of the project have also been successfully used in a course required by students majoring in ECE that is titled ECE 2723—*Electrical Circuits*. Course evaluations showed that many of the ECE students who used the "lab in a box" kit in ECE 2723 had a great appreciation of the hands-on pedagogy. The level of engagement was also noticeably higher when the ECE students used the kits (shown in Appendix I—Fig. 1) in class. In a similar fashion, the "lab in a box" concept in this work can be readily applied to other types of circuits courses and it would also likely be an effective pedagogy in courses that aren't focused solely on electrical circuits. Emphasizing hands-on skills, team/collaboration, and design experiences is of vital importance for today's engineering students and something that all courses should strive to include in their learning objectives. This study showed that Project Infinity effectively added these learning objectives in an innovative and engaging way.

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Appendix I—Detailed Information About Project Infinity

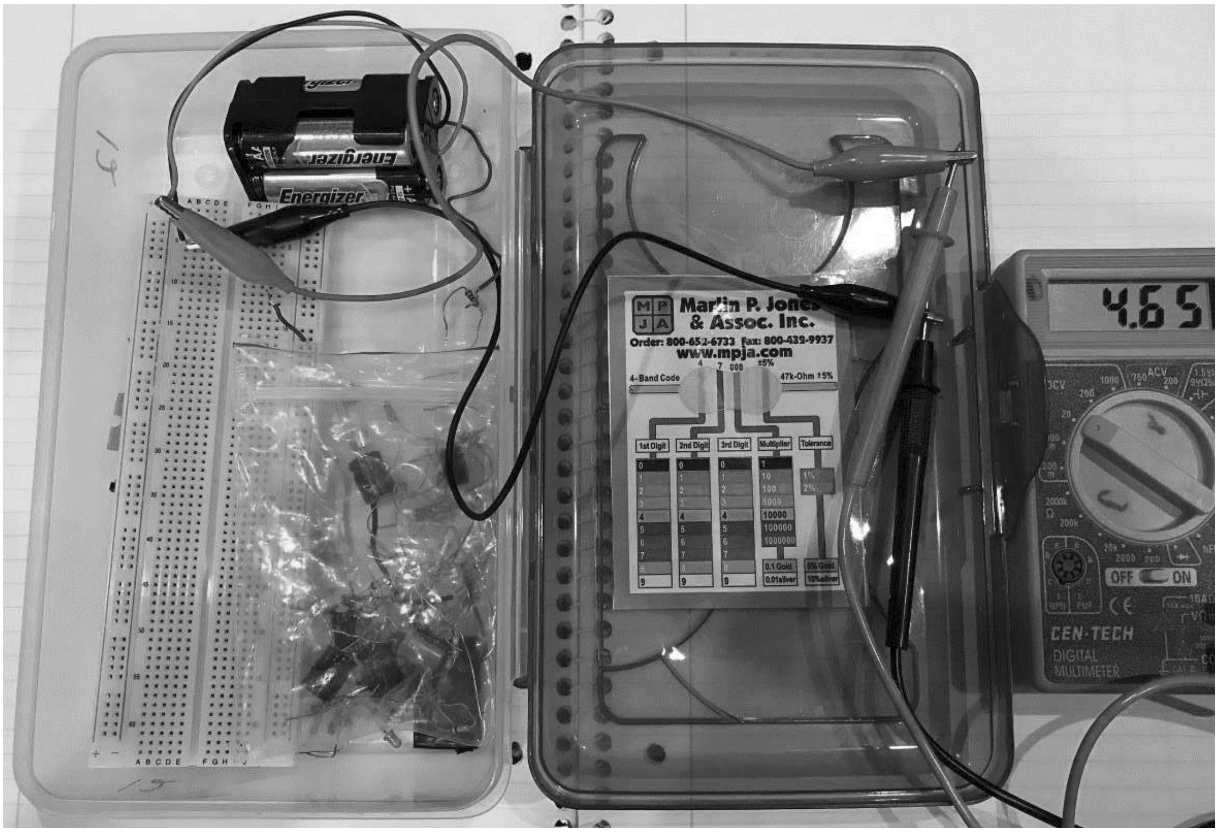

Fig. 1. Project kit with battery holder being measured (some items not shown). This figure shows the kit overlaid on a spiral notebook, which illustrates how it can be used on a desk with a small table top. The kit includes a breadboard, 2 AAA battery holders, alligator clips, a multimeter, screwdriver, and the following components: switches, potentiometers, LEDs, switching diodes, thermistors, Cadmium Sulfide Cells, phototransistors, inductors, capacitors, and resistors.

Exercise Descriptions for Project Infinity Part 1 – Basic Resistor-Based Circuits

(1) Battery pack voltages are measured with the multimeter.

(2) The resistors in the kit are measured using the multimeter, and the nominal resistance values are determined using the color code chart. In addition to these measurements, the students are asked theoretical questions to calculate the resistance of different material types and geometries at different temperatures.

Note: For most parts of the project the students perform calculations and compare them to the measurements and Multisim simulations. There are also many add-on theoretical questions in the project so that the theory can be blended with the practical application in a seamless way. For brevity, the circuits are described for the rest of the exercises, but some procedural details are left out.

(3) A circuit is built with resistors in series from a provided schematic and the voltage across both resistors and the current flowing in the loop are measured.
(4) The previous circuit is modified to include different resistors and a potentiometer. The potentiometer is adjusted until the voltage across it reaches a set value.
(5) Another single-loop circuit is built, but this time the two battery packs are connected to produce a voltage of six AA batteries in series, and a push button switch is used to turn on/off current flow.
(6) A circuit with a green LED is built and simulated in Multisim. Resistor values are then changed to different values to see the effect on the LED brightness. The LED is also turned around to show what happens when it is reverse-biased. A 1N914 switching diode is then used instead of the LED so that the voltage drop difference between the two types of diodes can be compared.
(7) A Cadmium Sulfide (CdS) photo-resistor cell that functions like a variable resistor that drops in resistance as more light shines on it is added in parallel with the LED so that it dims as more light shines on the CdS cell.
(8) An infrared (IR) LED and phototransistor are connected so that the voltage can be measured when breaking the beam of IR light by inserting an object between the IR LED and the phototransistor.
(9) The custom multiple-loop circuit in Fig. 2 (shown later in the document) is built. The total resistance in the circuit, supply current (XMM1), and the voltage at a specified node (XMM2) are measured. Numerous calculations are also required in this final exercise of Part 1.

Exercise Descriptions for Project Infinity Part 2—Advanced Resistor-Based Circuits

(1) Two-loop circuits (mesh analysis): A two-loop circuit that includes resistors and diodes is built and simulated.
(2) Three-loop circuits (mesh and nodal analysis): Additional complexity is added to the previous exercise so that the calculations become more complicated and the matrix solving techniques taught in the class are even more advantageous. After the students solve the circuit with mesh matrix analysis, source transformations are performed so that nodal matrix analysis can be performed. Note that the unique methods used to perform mesh and nodal matrix analysis are covered in [24].
(3) Designing a dimmer circuit: A multiple-loop circuit is built and resistor values are adjusted so that the LED current is changed to different specified current levels when the potentiometer is adjusted from end to end.
(4) Designing a circuit with a thermistor: Similar to the CdS cell used in part 1, a thermistor is frequently used in a voltage divider configuration to turn on a fan, light, or other devices. A voltage divider circuit is designed/built that has an output voltage greater than 2 V when heated and less than 2 V at room temperature. The schematic of the circuit including the transistor is provided so that only the values and structure of the resistor network need to be determined.
(5) Superposition: The circuit shown in the schematic of Fig. 3 (shown later in the document) is built. Resistor values in the circuit are adjusted so that the voltage across the three diodes is approximately the same value as one of the battery packs ($\sim$4.8 V). Next, the circuit is broken down into two subproblems and the XMM1 voltage is measured and calculated for both sub-problems:
   - Sub-problem 1—the three diodes that act like a 4.8V battery are short out.
   - Sub-problem 2—the 9.6 V battery is shorted out and the three diodes are replaced with a battery pack that is approximately equal to 4.8 V.

   Due to the superposition principle, the voltage across the resistor of the original circuit (XMM1) should be equal to the sum of the voltages in the two sub-problems.
(6) Thevenin equivalent circuit: A custom circuit is created in Multisim with a 9.6 V power source that has four loops, five to seven nodes, and between eight and ten resistors. One of the resistors is then removed and the Thevenin equivalent circuit is found "external to" the removed resistor. Resistors are selected for the circuit so that the Thevenin equivalent voltage (Vth) is between 2 V and 4 V and the Thevenin equivalent resistance (Rth) is between 1 kΩ and 5 kΩ.

Exercise Descriptions for Project Infinity Part 3—RL, RC, and RLC Circuits

(1) A schematic of a single loop circuit with a 9.6 V battery, push button switch, capacitor, and resistors is provided. Transient analysis (the time it takes for the capacitor to charge to a specified voltage) and steady-state analysis (the switch is held down until all voltages are constant) are performed. Capacitors are also combined in different configurations and the transient analysis is repeated.
(2) RC charging and discharging: The circuit in the schematic of Fig. 4 (shown later in the document) is

provided and the capacitors are charged by pressing Switch S1 until they reach the battery voltage level. Next, the capacitors are discharged by holding down Switch S2 so that the green LED turns on for a brief moment and then dims until it turns off.

(3) RLC steady-state analysis: A three-loop circuit with resistors, capacitors, and inductors is built and steady-state analysis is performed. The inductor current and capacitor voltage are used to calculate the stored energy.

(4) RC Low Pass Filter (LPF): A multiple-loop circuit that is set up as an LPF is built to show how the DC voltage (which is the lowest possible frequency) is passed on to the load resistor at steady state.

(5) RC High Pass Filter (HPF): A three-loop circuit that is set up as an HPF is built to show how the DC voltage is blocked and the voltage across the load resistor is equal to 0 V at steady state.

(6) The final exercise tests the students' intuition of how inductors work at steady state and how resistance changes impact voltage readings. The three-loop HPF circuit of the previous exercise is first used and the multimeter is set to measure the voltage across the load resistor. Next, two resistors in the circuit are replaced: one is replaced with the inductor and the other with the CdS cell. The goal is to put the inductor and CdS cell in locations where the light level of the CdS cell can be modified so that the capacitor voltage is between 45% and 55% of the capacitor voltage that was measured in Exercise 5.

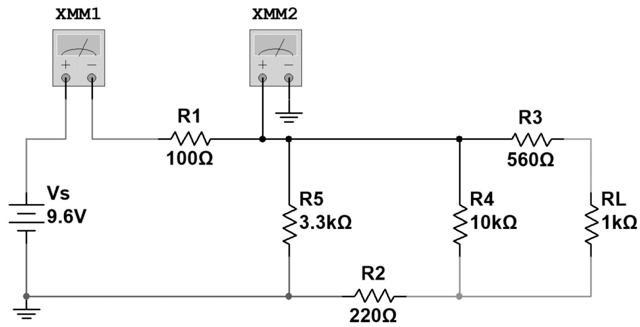

Fig. 2. Schematic provided for Exercise 9 of Part 1 of Project Infinity. XMM1 represents a multimeter making a current measurement and XMM2 represents a Mustimeter making a node voltage measurement. The 5 nodes in the circuit are color coded.

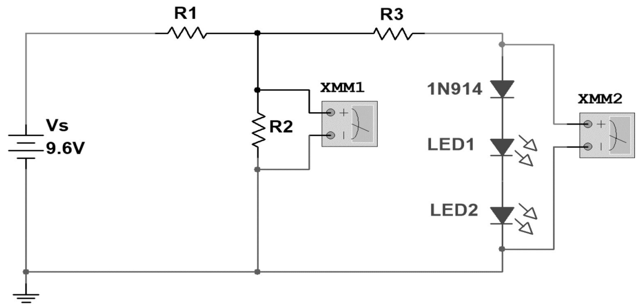

Fig. 3. Schematic for Exercise 5 of Part 2 of Project Infinity (Circuit used to apply superposition). XMM1 represents a multimeter measuring the voltage across resistor R2 and XMM2 represents a multimeter making a voltage measurement across two LEDs and a switching diode.

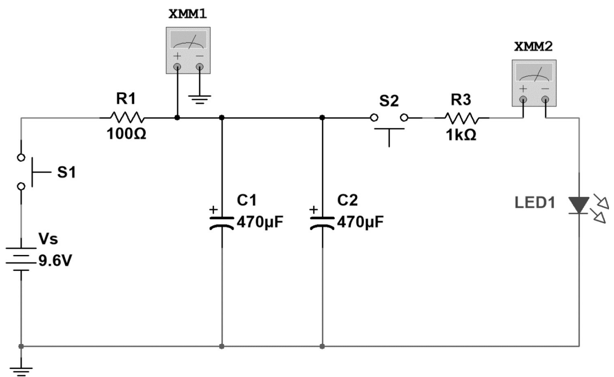

Fig. 4. Schematic for Exercise 2 of Part 3 of Project Infinity (RC charging and discharging circuit). XMM1 represents a multimeter making a node voltage measurement, which is also the voltage that the capacitors are being charged to as switch S1 is pressed. XMM2 represents a multimeter measuring the current as switch S2 is held down and the capacitor discharges across the LED and resistor, R3.

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