2018 ASEE Annual Conference & Exposition, June 24–27, 2018, Salt Palace Convention Center, Salt Lake City, UT

Paper ID #22770

Experiment-centric Pedagogy in Circuits and Electronics Courses

Prof. Kenneth A. Connor, Rensselaer Polytechnic Institute

Kenneth Connor is a professor in the Department of Electrical, Computer, and Systems Engineering (ECSE) at Rensselaer Polytechnic Institute (RPI) where he teaches courses on electromagnetics, electronics and instrumentation, plasma physics, electric power, and general engineering. His research involves plasma physics, electromagnetics, photonics, biomedical sensors, engineering education, diversity in the engineering workforce, and technology enhanced learning. He learned problem solving from his father (who ran a gray iron foundry), his mother (a nurse) and grandparents (dairy farmers). He has had the great good fortune to always work with amazing people, most recently professors teaching circuits and electronics from 13 HBCU ECE programs and the faculty, staff and students of the Lighting Enabled Systems and Applications (LESA) ERC, where he is Education Director. He was RPI ECSE Department Head from 2001 to 2008 and served on the board of the ECE Department Heads Association (ECEDHA) from 2003 to 2008. He is a Life Fellow of the IEEE.

Dr. Paul M. Schoch, Rensselaer Polytechnic Institute

Dr. Paul Schoch is an Associate Professor in the Electrical, Computer, and Systems Engineering department at Rensselaer Polytechnic Institute. His teaching includes the circuits and electronics sequence in his home department as well as an instrumentation course for non-electrical majors and an embedded control course available for all engineering majors. His research is in diagnostics for high temperature plasma. He is the director of the Center for Initiatives in Pre-College Education, a K-12 outreach arm at Rensselaer.

Kathy Ann Gullie Ph.D., Gullie Consultant Services

Dr. Kathy Gullie has extensive experience as a Senior Evaluator and Research Associate through the Evaluation Consortium at the University at Albany/SUNY and Gullie Cnsultant Services/ZScore. She was the principal investigator in several educational grants including an NSF engineering grant supporting Historically Black University and Colleges; ”Building Learning Communities to Improve Student Achievement: Albany City School District” , and ”Educational Leadership Program Enhancement Project at Syracuse University” Teacher Leadership Quality Program. She is also the PI on both ”Syracuse City School District Title II B Mathematics and Science Partnership: Science Project and Mathematics MSP Grant initiatives. She is currently the principle investigator on a number of grants including a 21st century grant and an NSF Transformong Undergraduate Education in STEM grant.

Dr. Dianna Newman, University at Albany-SUNY

Dr. Dianna Newman is a research professor at the University at Albany/SUNY. Her major areas of study are program evaluation with an emphasis in STEM related programs. She has numerous chapters, articles, and papers on technology-supported teaching and learning as well as systems-change stages pertaining to technology adoption.

Dr. Shayla Sawyer Armand, Rensselaer Polytechnic Institute
Dr. Jeffrey Braunstein, Rensselaer Polytechnic Institute

Abstract

Beginning in the late 1990s, the Electrical, Computer, and Systems Engineering (ECSE) Department at Rensselaer Polytechnic Institute implemented hands-on studio-based pedagogy by building and equipping special purpose classrooms supporting lectures, experimentation, and computer simulation. While learning outcomes were excellent, very high costs and limited space access made it impossible to realize the full potential of the approach. Both of these barriers were removed by the development of the Mobile Studio which put highly capable personal instrumentation in the hands of students for application any time and any place enabling the implementation of Experiment Centric Pedagogy (ECP) throughout the Electrical and Computer Engineering programs and in a service course for other engineering disciplines. With the recent addition of a new first year ECSE course, a sequence covering all four undergraduate years now exists which includes courses in Circuits and Electronics and capstone design. This combination of multiple courses provides many opportunities to study the impact of ECP on transfer of learning from one course to another and several other research questions including whether or not personal instrumentation makes it easier for students to learn the fundamentals of measurement. Possibly the most powerful outcome of ECP is that learning experiences can be significantly more authentic. In the intro Circuits course, for example, students are offered the option of either doing traditional, step-by-step procedural labs or a new type of design-based lab, with both sequences addressing all course content. Finally, the general engineering electronics course provides a compressed version of the ECSE sequence which permits transfer to be addressed quickly for comparison purposes. In this paper, results from internal and external evaluation of student and instructor feedback via observation, interviews, survey and content assessment will be addressed.

Background

The core undergraduate Circuits and Electronics sequence at RPI has focused on hands-on, student-focused instruction since the mid-1990s when studio-based pedagogy was implemented in dedicated classrooms that supported lecture, lab, simulation, and recitation activities. While learning improved significantly [1], the cost and access limitations of the studio classrooms inspired the development of the Mobile Studio to make it possible to utilize studio instruction anywhere and anytime. Three courses were involved in this effort, two in the Electrical and Computer Engineering Programs (Electric Circuits and Introduction to Electronics) and a more general Electronic Instrumentation course for other engineering majors. Electric Circuits is a pre-requisite for other core courses in Electromagnetics and Signals and Systems. For Electrical Engineering students, Electric Circuits is typically taken in the 2nd year and Introduction to Electronics in the 3rd. For Computer Engineering students, they are both taken in the 3rd year. Recently, a 1st year course has been added (Introduction to ECSE), replacing an Introduction to Engineering Analysis course that was largely Statics but also included a significant amount of Matrix Arithmetic.

Each of these courses is organized differently, but each has significant hands-on activities built around personal instrumentation, most recently the NI/Digilent Analog Discovery, and the usual open shop and office hours [2-8]. All except Introduction to Electronics are flipped/blended classes with video lecture materials, online (LMS) homework, an online question and answer platform (Piazza), team experiments and projects, homework involving experiments, etc. Section size generally varies from 30 to 60 and has recently become as large as 80. TA support, both graduate and undergraduate is provided for both in-class interaction and grading. At present, Digital Electronics is not part of this effort, although it does have a modified, studio-style organizational structure, as do Electromagnetics and Signals and Systems. The use of personal instrumentation and flipping the classrooms have made it possible to try out some creative new approaches to course delivery. It has also been possible for faculty to switch easily between these courses, which encourages the sharing of new ideas and allows faculty to easily see if what is done in one course has a positive or negative impact on subsequent courses. One instructor is now teaches all of the courses between the fall, spring and summer terms. Finally, the use of Piazza provides a record of how new pedagogical ideas are being handled by students.

This paper includes key observations from the Piazza record, observations from the instructors, and descriptions of some of the unique learning activities that have recently been developed for Electric Circuits, which remains possibly the most important course in the undergraduate programs because it is the pre-requisite for nearly every sub-disciplinary track. Actively sharing tools and ideas, alternating teaching assignments and fostering a culture of creativity in the classroom clearly makes for a better and more authentic engineering experience for students, teaching assistants and instructors. Engineering should be hard fun.

Observations from Piazza Questions and Answers

To provide some context for the student to student and student to instructor dialog recorded on Piazza, we look to Bloom's Taxonomy. The reason why Bloom's is so relevant is summed up rather nicely in a 2004 ASEE paper [9]. Their work precedes the availability of personal instrumentation, but they were moving in a good direction by arguing for addressing and assessing at all Bloom's levels rather than just the bottom three, which has typically been the case in traditional courses. They drew a general distinction between the top three and bottom three levels and identified which part of their testing corresponded to the lower and higher levels. They described levels 1-3 of the original Bloom's pyramid (Knowledge, Comprehension and Application) as focusing on whether students know and can apply the basic tools they learn in circuits. They then addressed integration of ideas, design and evaluation and, finally, applying concepts to new problems and problems they developed to assess how students have done at the upper Bloom's levels (Analysis, Design and Evaluation). We will make the same distinction between activities developed for the bottom three and the top three levels in the Revised Taxonomy. They redesigned their course so that class exercises put more emphasis on design and evaluation, with questions addressing both lower and upper Bloom's levels, with significantly more emphasis on upper levels than in the past. It would be reasonable to conclude that this made the course more challenging, but they found the students performed better and course ratings improved. Their results should apply equally if revised Bloom's levels are used. Therefore, in the following, issues raised by students will be generally described as relating to lower or upper Bloom's levels.

Studio-based pedagogy enables students and instructors to address essentially every topic using three complementary approaches. First, there is the traditional theory with paper and pencil problem solving. Second, there is experimentation using either benchtop or mobile personal instrumentation. Finally, there is simulation using SPICE-base circuit analysis. The latter two offer ‘a specific form of constructivist learning, namely, scientific discovery learning.’ [10] The literature on the use of SPICE-based simulation is quite extensive compared to the use of personal instrumentation, and involves many of the same issues as experimentation, although simulations are limited by the completeness of the models used and very rarely include the effects of noise, variation in component properties, poor connections and other practical issues that occur when circuits are built from real components. Experimentation, on the other hand, while more realistic, usually cannot produce the wide variety of parameter information that is possible through simulation. For example, oscilloscopes, whether benchtop or personal instruments, measure voltage and not current. Thus, they cannot directly determine current and power, so there is a clear advantage to having students use both experiment and simulation when they are investigating circuits. From one of the more complete studies of how student simulation activities in circuits classes (using NI Multisim) relate to Bloom’s Taxonomy [11], we see that the ubiquitous task of verifying the theoretical description of circuit performance is definitely found in the lower three Bloom’s levels. When the students were asked to predict the cause(s) for a given fault in the observed circuit behavior and then simulate as validation, they were working in the upper three levels. Both of these tasks can also be done experimentally, but it may not be possible to fully identify the cause of the fault using only one approach. Finally, the time and frequency dependent data obtained for circuits using either method have similar formats and, thus, involve similar issues in doing them correctly. For example, triggering a scope (aka deciding when to start collecting data) and specifying time and voltage scales require very similar student thought processes in that they have to at least roughly predict outcomes or they won’t be able to generate data that make any sense.

Three courses make regular and active use of Piazza; Intro to ECSE, Electric Circuits and Electronic Instrumentation. The latter is not in the Electrical or Computer Engineering programs, so it will only be used to make general comparisons. Each term tends to divide into three sections. First, lasting 3-5 weeks is the intro period. The Intro course sees a lot of logistics questions – how the course works, how the hardware and software work, etc. – during this period. This is much less the case in the Circuits course, especially for students who took the Intro course. Students also begin to seriously help one another during the first few weeks of the term. Second, lasting the bulk of the term is the steady-state period. During this period students focus almost entirely on questions involving higher level Bloom’s concepts. Last, lasting 1-3 weeks, is the last minute panic period, during which there are more questions on logistics as students work to finish their required work and prepare for the final, if there is one. Only Circuits has a final. Because of the ballooning of Mechanical Engineering enrollments, the Electronic Instrumentation course is generally the largest of the three courses, usually with about 300 students per year. Intro to ECSE has about 150 students and Electric Circuits a bit more than 200 students per year.

Intro to ECSE: The average response time for questions was 23 minutes. During the intro period there are a lot of questions about course logistics, how to download and install software, grading, formatting issues for LMS homework, etc. Content questions, which occur throughout the semester, almost entirely focus on the upper three Bloom's levels. For example, one student struggled with using voltage divider basics to determine the internal impedance of a battery and/or the input impedance of a measurement device like the Analog Discovery. These questions were answered by instructors. Then a student had some difficulties with maximum power transfer. A couple of other students led the confused student through the derivation and application of the power transfer theorem. They did an excellent job and their answer was approved by instructors. Then, a student asked about triggering. Once it was clear that a useful response would have to be somewhat involved, one of the instructors wrote up a one-pager and posted it for all students to see. Most students in the class at least were observers in this dialog. Another student struggled to answer one of the LMS homework questions because they could not find the information they needed in course videos. It often takes students a week or so to get used to this delivery modality. Another student provided some simplified information on how to address the problem and then posted exactly where to find that and other information in one of the course videos. A student had problems figuring out the average of a PWM signal primarily because they were not sketching what the time-dependent signal looked like.

Similar types of questions continued throughout the steady-state part of the course, with grading re-appearing near quiz dates. Otherwise, very little was asked about logistics. The number of questions per day dropped a bit very likely because students got better at finding what they needed in the extensive collection of online resources. In the final part of the course, students work on a somewhat open-ended design project and, thus, need to have their ideas confirmed by others. They also panic a bit about grades and deadlines, and also about concepts that they realize they should have learned earlier, but did not. Thevenin's Theorem often presents problems like this. One of the Chinese students in the class was unable to find other supporting materials online until another Chinese student provided its Chinese name so it was easier to search online. Most of the students want to learn the material better than is often possible in such a broad introductory course, which usually leads to asking questions in class rather than posting them on Piazza.

Electric Circuits: The average response time for questions was 45 minutes. The longer response time experienced in this class did not seem to inhibit the quantity and quality of questions and answers. The very few logistics questions at the beginning of the term are from students who did not take Intro to ECSE and/or relate to the different version of SPICE used. In addition to lots of higher Bloom's level questions, there are some simple misconceptions addressed which show the willingness of students to ask questions they may have been too embarrassed to do so in the past. The questions are often actually deeper than they look. One example had to do with labeling the polarity of circuit components so that KVL and KCL can be systematically applied. Many students struggle with the idea that they can label components however they wish as long as they pay close attention to the meaning of their labels. Students struggle to identify the correct number of unknowns and equations. Also, as usual, errors creep into problem statements so students need to be able to recognize when that happens and pay attention when errors are noted by an instructor. Some students are able to go back and forth between the two versions of SPICE (OrCAD PSpice and LTspice) and check answers. Others only get confused by doing so. By the second week, other students were providing good answers. An area where they are particularly helpful is in solving the same problem multiple ways. First doing simultaneous equations then switching to matrices offers a lot of opportunities to get sign errors, for example. These are caught by good students.

In the middle part of the course, students struggle with modeling. Real inductors have parasitic capacitance and lots of resistance. Also, sometimes, checking results with some SPICE tool does not work because students either have not included everything or a mistake was made specifying the problem. A classic simulation question was answered well by another student whose output looked like someone had filled in the screen with a green marker and not like the nice square wave expected. They were able to figure out that their time scale was much too big. Getting students to understand how to set up simulations clearly pushes them into upper Bloom's levels because it involves prediction. Even trial and error requires some thought because students have to predict what parameter to vary.

Electronic Instrumentation: The response time averaged 15 minutes. It is possible to provide very rapid response to questions, if the TAs are enthusiastic about participating. This rapid response helped to eliminate any issues a minority of students had because they could not ask questions when watching video lectures. The overall depth and quality of questions generally reflected the status of the course as being outside the core interests of the students, who were mostly Mechanical Engineering majors.

Note that the use of something like Piazza seems to be critical to making flipped classrooms work. Students need to know that they have a mechanism for asking questions, no matter where or when they are working. Also, it encourages students to help one another. There is little competition for grades in these courses because standards are clear and students are reminded over and over that our goal is that, someday, everyone will earn an A. Piazza also provides a structure that facilitates students working on higher Bloom's level activities, because they are more open-ended and may have several acceptable solutions.

Instructor Observations

We have taken advantage of the broad perspective made possible by having one instructor who teaches all of these courses and others that involve related material and obtained the following observations. The additional courses include Introduction to Electronics and Embedded Control. Note that what has improved a lot or a little are things that have significant focus in these coordinated classes, with the exception of troubleshooting. There are materials provided on troubleshooting and TAs are instructed on how to guide students through the process. However, time is too often limited and the TA's should get additional training.

As you will see from this instructor's comments, students are now much better able to use the hardware and software, build circuits, make measurements, etc. than previously. They have a more sophisticated view of measurement, taking, for example, account of the real impact of sources and measurement tools on the operation of their circuits. They are more curious and tinker more, which suggests they are moving up the Bloom's pyramid. There remains a significant problem for many students in that, while they do a good job identifying what signals are important to measure/characterize, they still do not provide adequate explanations of the information contained in their data. This is such a general problem in engineering that we cannot recall a single presentation at ASEE involving the collection of experimental and simulated data that did not mention it.

Things that are going well: *Students are much more capable of implementing circuits on breadboards. This is true not just for Electrical and Computer Engineering students, but also seems to be true of Mechanical and Aero students in Embedded Control. I have taught the latter course for ten years now. When I first started teaching the class, very few students had done any breadboarding. There are some Powerpoint slides as an introduction and I typically spent about 10 minutes discussing breadboards and then had them build a simple LED/resistor circuit for practice. This semester, when I asked if anyone was not familiar with breadboards, not a single student raised their hand. That was a first. That said, there still were a couple students who did manage to wire components on the same row, but most students had no difficulty building our first hardware worksheet, many finishing within 20 minutes. That is a significant change from early experiences where many students would spend a couple hours and then still need to ask for help.*

Students are better at using (and finding) simulation tools. Students are becoming more adept at finding software tools they are comfortable using. A majority still use either OrCAD PSpice or LTspice, but even there, many are able to resolve their own problems (as long as they are not operating system based). For example, I did not know that the method LTspice uses for implementing dependent sources is a little strange, since I was only familiar with OrCAD's layout. They Googled and solved their own problem in a few minutes. Another excellent example in Embedded Control last semester was a student that implemented his own graphical simulation of the rotating gondolas (the physical system they are controlling). *While seeing a student do something like that is still fairly uncommon, it was still impressive seeing him take his coding experience and implement a numerical algorithm to model damping with a graphical display.*

Students are more aware that equipment/instruments can affect measurements and why. The laboratories about measuring internal resistance have certainly paid off. When I bring up the topic in Circuits, they are much more comfortable with the practical concept that a resistor exists in series with a source, as opposed to some arbitrary concept that we teach them on paper. In both Intro to Electronics and Circuits, I typically include equipment/component property questions on the final exam. Nearly all students recognize that measurement probes are typically high resistance and other related questions. Not as many understand the capacitance implications, but that is understandable. That said, despite repeated reminders, they do forget the effects of that impedance when presented with high impedance components on the circuit (as mentioned below).

Students are more curious about what they are seeing. Especially true in the first year course, where material is rapidly introduced. They want to have a better sense of underlying concepts *than that which is presented in laboratories. In the Intro to ECSE class, I do find that the more involved students are sometimes unsatisfied with the short attention we can give topics. A number of times I did stay late, trying to provide a deeper insight while not overwhelming them with math. At a higher level, I credit the Circuits Beta labs for strongly encouraging students to go beyond the classroom. I have tried a similar approach in Intro to Electronics, though, without quite the same incentives. I still have about 20% of the class doing extra work, some of which is very creative and beyond the scope of anything I discussed in class.*

Things that are OK: *Students are somewhat better about attempting to find signals and scaling to see those signals. I think the fact that "Autoscale" is not obvious on the Discovery Board helps. However, they frequently forget about this over a 'summer break' and have to figure it out all over again. In Circuits and Intro to Electronics, I still have to remind students to change the horizontal and vertical scale to 'find' the signal, despite the fact that those same students used the Discovery Board a year earlier. It is less of a problem than it used to be, however, from my perspective it is the type of thing that should be obvious. The same can be said when they are asked to do simulations without any direct guidance. I have had simulations with source periods at 10kHz and students will run simulations at nanosecond or second scale, and then be baffled why their results are strange.*

Students seem to have a better idea why looking at a particular signal is important. The connection between measurement and theory is better. On the other hand, there still are a number of students who acquire data/measurement and just methodically include those results without paying attention to whether they are correct or not. The simulation pre-labs in Intro to Electronics are an excellent example of this problem. These exercises are designed to give students an idea of what they should see in the laboratories. Unfortunately, I have had a significant minority of students hand in simulation results that were garbage due to some major implementation error, ie. sources connected 'backwards' for an op-amp, etc. The results are problematic enough the students really should have known better than to hand them in. This includes plots that were so undersampled they looked more like abstract art than a simulation result.

Students don't always pay attention to when equipment is affecting their measurements. As above, they are aware of the possibility, but still miss it, even when it is very clear something is inconsistent. In the first Intro to Electronics lab, I have students use the benchtop function generators and set up a 1V amplitude signal connected to an op-amp circuit with an input impedance in the kΩ range. Unfortunately, I only have a few students ask why the inverting circuit is producing twice the expected output amplitude. When I explain about the 50 Ω internal impedance and display voltage characteristics, they still struggle making the connection to the voltage divider circuit. Likewise, when I use high resistance feedback resistors, only a few recognize the effects of the scope impedance unless it is pointed out to them.

Things where I want to see students improve: *Student documentation of their work is relatively poor. Too many reports copy and paste questions posed followed by very short* *answers. I would say this is a major problem. One of my favorite questions in the laboratory is, "Did you read all the words?". Students like to skip to the laboratory without reading any of the introductory discussion. On the same note, I have recently starting asking the students, "Did you write any words?". I have seen senior level reports in the Power Laboratory that were 20+ pages of images with less than a page of text. Unfortunately, this is a problem I have no idea how to address. In Embedded Control, I have actually campaigned to remove the impact of reports in the class. I am well aware of the importance of technical writing. In an academic setting, without significant oversight and resources, there is no realistic way to have them write their own reports (as opposed to using the internet, archived reports, etc.). I do stress the important of technical writing in the classes, but I leave the students to decide how dedicated they want to be.*

This is clearly a topic that needs further work. Not only does good writing make it easier for others to use the results obtained, it also adds significantly to learning. Mark McDaniel, one of the co-authors of *Making It Stick*, and his colleagues have produced some excellent research demonstrating that writing also enhances learning [12]. In the appendix to their paper, they offer a sample question that relates well to what we try to do with our engineering students in the lab. “Even after encoding information well, it is some-times still forgotten. 1. Draw the forgetting curve. 2. Explain (in writing) your drawing to someone who has never heard of it. Why does it have this particular shape?” The forgetting curve shows the exponential decay of a memory with time. The slope of this line can be changed by re-visiting the topic, which extends the memory.

Students still seem to have difficulty learning to troubleshoot. This ties into their repeated efforts to build complicated circuits on the first go rather than stage by stage. I see the same thing with code development. I typically spend a fair bit of time telling students to start small and build upward. Or even more basic, if you aren't getting a signal, measure the source itself and work forward. They seem to have a difficult time recognizing that they can do this themselves. In Embedded Control, output signals pass through a buffer gate before connecting to the LEDs/buzzers. The chips are cheap and gates frequently burn out. Despite a worksheet where they explicitly measure both sides of the buffer when it has been disabled, they don't seem to be able to correlate that going forward. It should take two simple measurements with a logic probe in about 15 seconds to diagnose the problem, instead of the very long time (sometimes hours) they spend trying to change their code.

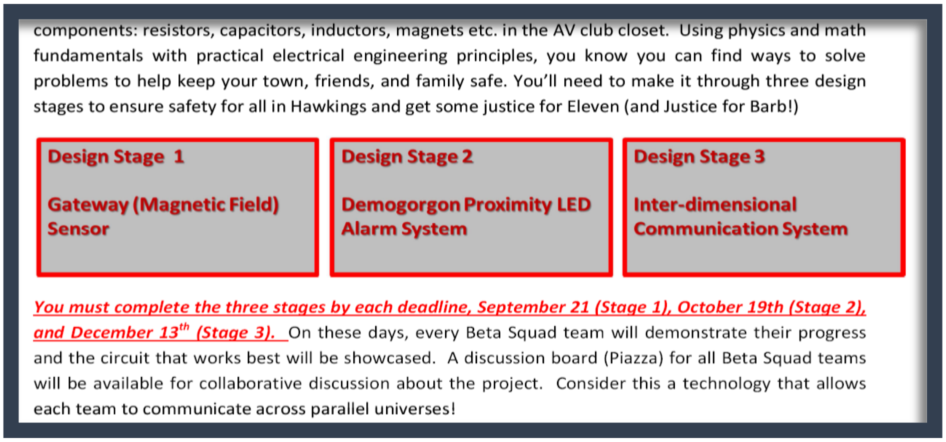
Students don't seem to understand why using a reliable input signal (source signal) as a reference is important.

Students are very comfortable with their toolset and enjoy being challenged by more design-driven experiences. They also are able to make building the complete circuit work often enough that they are not learning the value of the step-by-step procedure. They are very reluctant to dismantle things for testing. Clearly we have to push them further up the Bloom’s pyramid in this regard and in report writing.

Circuits Beta Labs

The broadly based sequence of circuits and electronics courses also makes it possible to implement other creative ideas. In a recent initiative at RPI, Circuits students have been given the option of a significantly more authentic learning experience by doing a series of semester-long design-based activities rather than more traditional experiments. Students find that they are learning how to solve real problems in electronics. Both students and teaching assistants show a significantly higher level of interest in and passion for the course. The instructor who has taught essentially all ECSE and engineering courses with substantive electronics content has found, as noted above, that these new *Beta Labs* strongly encourage students to go beyond the classroom. So much so that he is now working to implement similar experiences in the Intro to Electronics course.

In the Fall 2016 semester, students in Electric Circuits had the opportunity to use fundamental Electrical Engineering principles to find and enter an interdimensional gateway, in search of a lost friend while escaping a monster (Figure 1). In Spring 2016, brave students found themselves stranded on Mars with a need to find a way to communicate with Earth to return safely home. These Beta Design Laboratories were a pedagogical tool introduced as an option to replace the traditional step-by-step instructional labs (called Alpha Laboratories). Students had a choice of completing either 13 traditionally procedural Alpha Labs during the semester or 3 Design-Based Beta Labs. The content covered in both lab sequences during a unit was the same, but the integration of those concepts to solve a specific problem was specifically emphasized in the Beta Lab, as shown in Figure 2. Also, proactivity and full autonomy was required as often students often needed to design solutions based on concepts not yet fully introduced in the lecture. The success of this new pedagogical approach is best appreciated by reading comments from former students who have also served as undergraduate teaching assistants.


components: resistors, capacitors, inductors, magnets etc. in the AV club closet. Using physics and math fundamentals with practical electrical engineering principles, you know you can find ways to solve problems to help keep your town, friends, and family safe. You'll need to make it through three design stages to ensure safety for all in Hawkings and get some justice for Eleven (and Justice for Barb!)

Design Stage 1	Design Stage 2	Design Stage 3
Gateway (Magnetic Field) Sensor	Demogorgon Proximity LED Alarm System	Inter-dimensional Communication System

You must complete the three stages by each deadline, September 21 (Stage 1), October 19th (Stage 2), and December 13th (Stage 3). On these days, every Beta Squad team will demonstrate their progress and the circuit that works best will be showcased. A discussion board (Piazza) for all Beta Squad teams will be available for collaborative discussion about the project. Consider this a technology that allows each team to communicate across parallel universes!

Figure 1: Introduction, narrative, and preview of design stages for the Fall 2016 Beta Design Labs.

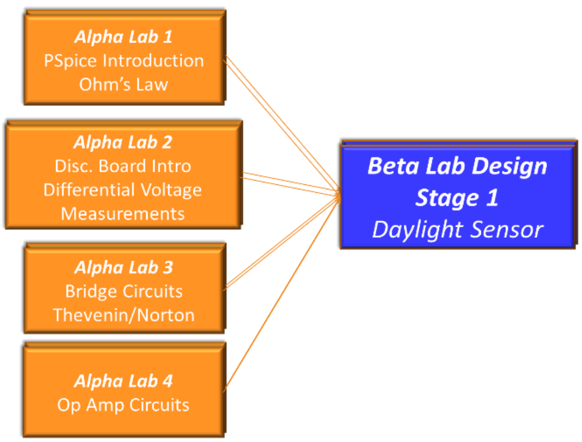


Figure 2: Example of how one Beta Design Stage (Daylight sensor) has components corresponding with four traditional Alpha Labs in Unit 1 of Electric Circuits.

The Beta Design Labs were an organic progression of thoughts and ideas that culminated from the instructors experiences with students at the bookends of their education. First, was involvement with the NSF Graduate Teaching Fellows in Community-Situated Research Program, which provided numerous discussions about how to break down complex, research concepts for the middle school or high school classroom and solving a problem in an interesting context left a lasting impression on students and encouraged deeper learning [13].

Second, involvement in a senior level capstone design course motivated the idea to bring design in the context of a course very early in the students' curriculum. Capstone design students tended to compartmentalize their learning across many areas and could not see the connection between concepts in their varied courses. Their lack of confidence in finding these connections hindered their ability to efficiently and effectively solve the open ended problems that define the work in a multidisciplinary capstone project. As a result of this, the Beta Labs were developed to provide a context and a framework for students to willingly participate in a laboratory that encourages creativity but also requires thorough communication as to how their solution specifically relates to concepts learned in the course. Furthermore, they must go through the engineering practice of providing analytical calculations, simulations, and experimental data and comparing them to prove that their solution does indeed solve the problem. This moves them away from the mentality of simply trying to match the answer of a professor. The Beta Design Labs are also enabled by online resources and personal instrumentation (Analog Discovery Board) purchased by all students at the beginning of the course. Autonomy is encouraged throughout the course and these resources helped to provide them needed access to information and necessary equipment at anytime and anywhere.

Five former Electric Circuits' students, all of whom also subsequently worked as Teaching Assistants in the class, were asked to provide their observations on what made the class work. All students had excellent comments on the outstanding experience they had as students and helping other students. One student, described the instructor as *an extremely knowledgeable and charismatic professor … (who) … repeatedly demonstrated a willingness to go the extra mile for her students, whether that means holding extra office hours, embracing new technologies to assist in student learning, or redesigning curriculum to provide the greatest education value.* He said, what he particularly found valuable about the learning experience was her ability to provide a *connection between the course work and real world applications … reinforced through homework and exam design problems.* In his second semester as an Undergrad TA, the Beta Labs were introduced. As he described the experience …*while the paper design problems forced students to consider various theoretical aspects, the actual construction of these systems provided an introduction into issues faced constantly by industry prototype and manufacturing teams. I helped teams debug problems caused by ground loops, noise accumulation, chip defects, static damage, temperature variations, and part availability. In all cases, once a team had successfully solved the seemingly mystic issue two things happened. First they were overjoyed in having overcome their newly unmasked foe, and second they learned a lesson that would be with them for the rest of their professional careers.*

Another student said *that the Beta Labs are a revolutionary way of teaching circuits here at RPI. They … go far beyond the usual goal of merely providing a hands-on experience and actually help students to learn how to solve real problems in electronics. In many classes here, there is an abundance of theory and ample opportunity for observation. Much rarer … is there a focus on the design process and design skills which out of everything students will learn … is probably the most useful for their future careers.*

A third student that the classes are structured *in a very innovative and effective way for the students. Every lecture was posted online, allowing students to watch and re-watch the lectures in their time and as needed. The class time was then focused on what the students gave as feedback for the more difficult topics and example problems. My peers and I found this to be a much more helpful way of using time.* This student and her partner were in the second semester of the Beta Labs experiment. She said that *my lab partner and I participated in these and I can easily say they have had the biggest impact on my learning techniques and abilities of anything I have done in my other classes thus far. I learned to be proactive in my learning, to fight to learn on my own … to write full and comprehensive lab reports, and to take pride in my work through the presentation of my design.*

Another student was both *a* Circuits student as well as a Graduate Teaching Assistant. *As a student that had no practical experience with circuitry in any form, I began my undergraduate career with difficulty understanding not only the general concepts of electric circuits, but how they were applied in a practical sense. The method of teaching* (in Electric Circuits) *ensures* *students learn problem solving skills, and a deeper understanding of how electrical engineering relates to applied problems in the world, rather than memorization for improved test performance… The creation of the Beta Labs … has redefined the Circuits course at RPI… This pushed students to spend more time researching, and not just accept an answer given to them, but instead find out why. By the end of the first Beta Lab students told me how they appreciated being guided to further their research as opposed to being just told an answer…*

The last student particularly saw value in the recorded video lectures. *One of my favorite part of* (the) *class is the lecture videos …* (which) *explains some of the basic concepts and reviews example questions consistently during the entire semester… I have known several students who struggle a lot at RPI but make huge achievements in* (this) *class… I was there for the first semester* (of) *the Beta Lab and had seen huge success due to this innovation… The labs are challenging in a fair level, and really bring a lot of testing and thinking that can even benefit the students with a lot of experience. According to the student feedbacks, the work load is pretty reasonable and the labs are really fun to work with.*

Each year the Beta Labs are updated to be based on a new topic. Evolving from *Stranger Things* to *The Martian* to now *Wall-E*. A copy of the most recent Beta Lab instructions is attached.

Summary

Offering core Electrical and Computer Engineering courses in a coordinated sequence built on personal instrumentation enabled studio-style pedagogy, makes it possible for instructors to easily switch between courses, share ideas and promote a culture of innovation. Students have a more authentic engineering learning experience and are able to push their learning as far as they desire in each course. Students lose less time becoming comfortable with experimental equipment and, in fact, find new instrumentation easier to work with. Continuous improvement is facilitated because there is so much readily available information on how well ideas work in a course and the impact they have in subsequent courses. Students and TAs also get to contribute to making everyone's learning experience better.

There is still much work to be done, but this course structure actively enables continuous improvement. While students are successfully helped to approach problem solving through the use of all tools available to practicing engineers, including basic theory, paper and pencil problem solving, experimentation, simulation, and system level model development on problems that are increasingly more real-world, they still struggle to fully compare and contrast the results from each approach and to present the full story contained in the data they collect. They are moving further up the Bloom's pyramid, especially with the additional design-driven learning experiences now available in Electric Circuits, while still solidly learning their ECE fundamentals. As we continue to get better at this kind of coordinated educational delivery, we will be able to further nudge them in this direction.

Acknowledgement: This material is based upon work supported by the National Science Foundation under Grants EEC-0812056 & DUE-0717832

References

[1] E. Maby, B. Carlson, K. Connor, W. Jennings, P. Schoch, *A studio format for innovative pedagogy in circuits and electronics* Proceedings - Frontiers in Education Conference, Dec 1997

[2] M. Chouikha, & D. Millard, *Toward the Development of a Mobile Studio Environment* Paper presented at ASEE Annual Conference, Portland, June 2005. https://peer.asee.org/14984

[3] J. Coutermarsh, & K. Connor, & D. Millard, *Re Engaging Engineering Students in Hands-On Education* Paper presented at 2006 Annual Conference, Chicago. https://peer.asee.org/1115

[4] K. Gullie, D. Newman, K. Connor, M. Chouikha, (June, 2016). *The Impact of a Technology Based Mobile Hands-on Pedagogy on Student Learning, Course Design and Faculty Perceptions of Use in STEM Education.* A paper presented at the 2016 Ed Media Conference, Vancouver.

[5] K. Connor, K. Meehan, B. Ferri, A. Ferri, D. Walter, *Center for Mobile Hands-On STEM*, Paper presented at ASEE Annual Conference, Columbus, June 2017 https://peer.asee.org/27814

[6] K. Connor, D. Newman, K. Gullie, M. Chouikha, P. Andrei, J. Attia, O. Nare, Y. Astatke, L. Hobson, R. Bowman, K. Heidary, A. Eldek, S. Albin, S. Zein-Sabatto, J. Kelly, P. Matin, *The Implementation of Experiment Centric Pedagogy in 13 HBCU ECE Programs,* First Year Engineering Experience Conference, Daytona, August 2017

[7] K. Connor, D. Newman, K. Gullie, P. Schoch, *Faculty Development and Patterns of Student Grouping in Flipped Classrooms Enabled by Personal Instrumentation*," Paper Presented at ASEE Annual Conference, Columbus, June 2017 https://peer.asee.org/28351

[8] D. Newman, M. Deyoe, K. Connor and J. Lamendola, (2014) *Flipping STEM learning: Impact on students' process of learning and faculty instructional activities* in S. Keengwe, G. Onchwari & J. Oigara, (Eds) Promoting active learning through a flipped classroom model (pp. 113-131) Hershey, PA: IGI Global

[9] R. Thomas, and A. Rosa. (2004, June), *A Proven Different Approach To Teaching Linear Circuits* Paper presented at 2004 Annual Conference, Salt Lake City. https://peer.asee.org/14050

[10] T. de Jong and W. R. van Joolingen, *Scientific Discovery Learning With Computer Simulations of Conceptual Domains*, Review of Educational Research, vol. 68, 1998.

[11] G. Banky and K. Wong, *Troubleshooting exercises using circuit simulator software: support for deep learning in the study of electronic circuits,*" International Conference on Engineering Education – ICEE 2007, September 2007

[12] K. Gingerich, J. Bugg, S. Doe, C. Rowland, T. Richards, S. Tompkins and M. McDaniel, *Active Processing via Write-to-Learn Assignments: Learning and Retention Benefits in Introductory Psychology,* Teaching of Psychology, Vol 41, 2014.

[13] R. Eglash, W. Babbitt, A. Bennett, K. Bennett, B. Callahan, J. Davis, J. Drazan, et al (2016). *Culturally Situated Design Tools: generative justice as a foundation for STEM diversity*. Pp.

132-151 in Y. A. Rankin and J. O. Thomas (Eds.), Moving students of color from consumers to producers of technology. Hershey, PA: IGI Global.