# Bottlenecks and Muddiest Points in a Freshman Circuits Course

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# Bottlenecks and Muddiest Points in a Freshman Circuits Course

**Abstract:** This paper describes the bottlenecks and "muddiest points" found in a freshman circuits course and methods developed at the University of Utah to address them. The 4-credit semester-long course is a typical first circuits course with lab, including coverage of op amps and sensors. The final lab project is an invention of the student's choosing -- a resistive or capacitive sensor circuit that utilizes the course concepts as well as open-ended design and system concepts.

Determination of bottlenecks and muddiest points was done through weekly muddiest point assessements, exams, quizzes or self-assesments, and online feedback. Solutions to address the bottlenecks included providing applications and real-world examples, providing step-by-step cookbooks, color coding circuit nodes, organizing the circuit design equations into a circuit analysis toolbox, using a deck of cards representing the functional design of a system, and creating a library of in class demos. These improvements, along with the use of a flipped classroom and incorporation of a National Instruments myDAQ device, resulted in an increase in the pass rate of the class.

## I. Introduction

Students in an introductory circuits course have a variety of challenges. Some of these arise from the course content. Bottlenecks or threshhold concepts [1] are basic concepts that are fundamental to more advanced concepts. Muddiest points [2] are concepts that remain confusing even after the lecture/class time. If many students express the same confusion, the instructor may need to provide additional resources or explanation. Challenges outside of course content (such as time management) are life or learning challenges that pervade the student experience.

This paper describes the bottlenecks and muddiest points in a freshman circuits course, and methods that may help alleviate them. This 4-credit semester-long course is taught in a flipped format, with short (roughly 15 minute) video lectures prior to class and active learning in the face-to-face class. Assessments included traditional exams as well as weekly Muddiest Point reflections and/or quizzes and self-assessments, and online learning and course feedback every 3 weeks. These assessments provide a window into the most common challenges students faced throughout the semester, which we report in this paper.

The following sections discuss the assessment methods, bottlenecks, muddiest points, and challenges identified in the course, and methods the instructors developed to help students overcome them.

### A. Course content

ECE 1250 Introduction to Electrical and Computer Engineering (ECE) [3] is a 4-credit semester-long (15 week) course required for freshman ECE majors at the University of Utah. It covers

Ohm's law, voltage and current through resistive networks, analysis methods (Kirchhoff's laws, node voltage method, Thévenin/Norton equivalents, etc.), op amp circuits, RLC circuits and a brief introduction to digital circuits. In addition, the course covers Matlab basics, and "what is" Electrical and Computer Engineering. It is taught in three 50-minute sessions per week in a stadium-style classroom, in fall, spring, and summer by three different professors, with typically 60, 80, and 20 students, respectively. The course uses the free online textbook Circuits [4] by Ulaby, Maharbiz, and Furse. Content from the course, including videos, lecture notes, old exams with solutions, labs, etc. is available open source at [3]. Content specific to instructors, such as in class exercises, is available to instructors upon request.

In 2014, the course was updated. Lectures were flipped (pre-class online videos replace traditional class lectures), and class time is used for active learning, discussion, and questions. Lecture videos were created in short segments (3-5 minutes) per topic for a total of about 15 minutes per lecture.

A weekly lab (3 hours long) gives students hands-on experience with the course concepts. Groups of up to 20 students are taught by a student teaching assistant. The final lab project is an invention of the student's choosing -- a resistive or capacitive sensor circuit utilizing op amps. The National Instruments myDAQ device [5] is used to provide a personalized learning laboratory the students can use both at school and at home.

The course is divided into four topical units:

- Unit 1: Definitions, components, Ohm's law, Kirchhoff's laws, source transformations, voltage and current dividers.
- Unit 2: Node-voltage, superposition, Thévenin and Norton equivalent circuits.
- Unit 3: Op amp circuits, systems, digital logic.
- Unit 4: RL, RC, RLC circuits.

### B. Assessment

Both formative and summative assessments were used throughout the course to better understand the student experience and the most challenging concepts. Assessments included weekly muddiest point reflections and/or quizzes and self-assessments (depending on the professor), four exams, and online feedback (every 3 weeks).

#### 1. Muddiest Points (weekly)

In weekly written Muddiest Point assessments, students related the concepts they found most confusing that week, and tried to explain them. A small amount of extra credit was given (responses were not anonymous), and the professor collected and collated the (anonymized) responses via the classroom management system to create a frequently asked questions blog as well as responding to individual concerns or confusions. This helped the instructor understand what the students were struggling with throughout the course, and it also helped the students reflect on their understanding. Weekly self-assessments were also provided, so the students could voluntarily self-test their understanding. The muddiest or most confusing concepts will be discussed in Section II.

#### 2. Exams (4, plus make up final)

Four exams were given throughout the semester. These were traditional exams, typically 3-4 problems worked on paper. The grading distribution between the exams and finals was unique, however. The final was broken into four parts, each providing a make up opportunity for previous exams. Students could choose to take any parts, all, or none of the final. They were given the highest of either the exam score or the score on that part of the final. This is particularly motivational for the students, encouraging them not to give up and to work to learn material they are missing. This grading scheme has been used in a variety of classes, and is described in more detail in [6]. Errors on the exams were evaluated to determine areas students were still struggling with, and these are discussed in Section II.

#### 3. Online feedback (every 3 weeks)

In addition, feedback on the class and pedagogy was collected at approximately 3 week intervals to help the instructor monitor the student experience. Feedback was  optional, not anonymous, and a small amount of extra credit was given. The feedback was open ended (no likert type questions were used) and included the questions, “What can I do to help you learn better?” and “What can you do to help you learn better?”  This  provided a meaningful opportunity for students to reflect on their own learning techniques and behavior [7].

## II. Challenges

Some of the challenges in the course arise from the subject matter, as expected. Other difficulties arise from learning challenges such as time management, different learning styles and disabilities, algebra preparation, etc. In this section of the paper, we will discuss both types of challenges common in this course.

### A. Challenges with subject matter

Difficulties with the subject matter were gathered from muddiest point assessements and exam results, and are summarized in Table 1.

Table 1: Muddiest points and exam errors

| Unit 1: Definitions, components, Ohm's law, Kirchoff's laws, source transformations, voltage and current dividers | |
|---|---|
| Muddiest points | Exam errors (most frequent errors listed first) |
| • Current, charge, voltage, resistance, power, energy (What are these 'really'?)<br>• Getting the signs right (polarities (+/-))<br>• Grounding<br>• Series / parallel resistors<br>• Dependent and independent ideal/non-ideal voltage /current sources<br>• Node voltage vs. voltage difference<br>• Short circuits<br>• Kirchoff's laws, especially when to use them and how to set up the problems<br>• Matrix math for KVL/KCL<br>• How and when to use voltage and current dividers | • Transformation from Norton to Thévenin equivalent.<br>• Choosing which circuit equations are needed to solve the circuit.<br>• Converting circuit equations to matrix equation.<br>• Errors using calculator.<br>• Confusion about engineering units.<br>• Incorrect algebra.<br>• Assumed current source had zero voltage drop. |

| Unit 2: Node-voltage, superposition, Thévenin and Norton equivalent circuits. | |
|---|---|
| Muddiest points | Exam errors (most frequent errors listed first) |
| • What solution method to use and when<br>• Supernodes<br>• How to measure node voltages and voltage differences, and current<br>• Thévenin-Norton, $R_{Th}$, and why we would use this? Especially confusing with dependent sources.<br>• Superposition questions (why/when/how?) | • Inability to write valid expressions for currents in branches in node voltage method.<br>• Missing voltage equation for supernode.<br>• Two sources instead of one on at a time in superposition method.<br>• Sign errors. |

| Unit 3: Op amp circuits, systems, digital logic | |
|---|---|
| Muddiest points | Exam errors (most frequent errors listed first) |
| • Why does negative feedback work?<br>• What is gain?<br>• Why doesn't current go into an op amp?<br>• How to find the R's for a complicated op amp circuit?<br>• Voltage loading, and input and output resistance (when combining op amps into systems) | • Error designing logic circuit for given truth table.<br>Rarely occurring errors:<br>• Incorrect resistor ratio in amplifier design for specified gain.<br>• Unable to use Circuit System Design (CSD) cards [8] to find Thévenin equivalent of a circuit. |

| | |
|---|---|
| • Digital/analog (what it is, what is the difference, how to make the gates work?)<br>• How to connect gates to get a specific output? | |

| Unit 4: RL, RC, RLC circuits | |
|---|---|
| Muddiest points | Exam errors (most frequent errors listed first) |
| • What is low-pass and high-pass?<br>• How to calculate RL, RC circuits?<br>• How do they actually store charge?<br>• Sine waves, complex numbers/phasor analysis, impedance | • Problems with algebra of complex numbers<br>• Numerical calculation for impedance of capacitor or inductor (1/jωC and jωL).<br>• Incorrect circuit for time approaching infinity in RL circuit.<br>• Failed to use general exponential form of solution for RL and RC circuits.<br>• Incorrect circuit for time $t = 0^-$ for RL circuit.<br>• Error in numerical calculation.<br>• Error determining value of time constant in RL circuit. |

**B. Challenges outside of course content**

In addition to course content, many students struggle with problems such as time management, learning styles and disabilities, algebra preparation, etc. The assessments throughout the course have helped us understand many of these issues, more detail of which can be found in [7]. Time management was the most common problem identified throughout the semester. The online feedback showed many students were self-aware of the problems that were impacting their learning. The instructor often reached out to them or pointed them to university resources. Learning disabilities self-identified in the first-week assessment "Tell me something non-technical about yourself" have included dyslexia, autism spectrum, ADHD, color blindness, PTSD, and mild or profound deafness. The Center for Persons with Disabilities (CPD) provides specific recommendations for student accommodations and advice on teaching strategies.

Learning styles may also impact student success. In the first week, an extra credit assignment encourages them to take an online assessment, identify their learning styles using the Felder-Silberman model, and read about ways they may improve their learning [9]. A small amount of extra credit is given to describe their learning style and how they can optimize their learning. Particularly since this is a flipped course, we find that students select how they use the resources to (hopefully) best serve their individual needs. Most (>80%, according to analytics from our learning management system) watch at least part of the video lecture before class with no incentive other than instructor encouragement. When queried, most say they do this because it helps them learn. Some then read the book, others read it later or use it as reference material, and still others use it minimally or not at all. Some use office hours (TA or instructor), others prefer peer interactions. Most find the peer interactions in the active learning classroom valuable. A few do not. The instructors have adopted a number of teaching techniques to appeal to students with different learning styles and abilities. We report on the variation in how students choose to use the materials in [10].

## III. Learning tools for course content

In this section, we return to challenges with course content described in Section II, and describe learning tools we have developed to improve student learning. These include: providing applications and real-world examples to put content in context [3], providing step-by-step cookbooks, color coding circuit nodes, a Circuit analysis toolbox representing input and output variables for each method, using a deck of cards representing the functional design of a system, and creating a library of in class demos. Table 2 summarizes muddiest points from Section II and the learning tools used to improve understanding of that concept.

Table 2: Challenging concepts and associated learning tools

| | **Learning Tools** |
|---|---|
| 1 | Real-world examples |
| 2 | Color the nodes |
| 3 | Step-by-step cookbooks |
| 4 | Circuit analysis toolbox |
| 5 | Circuit System Design cards |
| 6 | In class demos |

| **Tool** | **Concept(s)** |
|---|---|
| 1-3 | Basics: ground, node, path |
| 2,6 | Voltage diff. vs. node voltage |
| 2,3,6 | Series/parallel resistors |
| 2,3 | Short circuits |
| 1,3,6 | Kirchoff's law |
| 1,3,6 | Voltage and current dividers |
| 2,3,6 | Node voltage method |
| 1,3,6 | Superposition |

| **Tool** | **Concept(s)** |
|---|---|
| 1,2,5,6 | Thévenin and Norton equivalence |
| 1,3,5,6 | Recognizing op amp configurations |
| 1,3,5,6 | Op amp design |
| 1,3,6 | Understanding RC circuits |
| 3 | RLC circuits |
| 4 | What solution method to use |
| 4 | Organizing the steps to a solution |
| 1,5 | Achieving an invention project |

### A. Coloring the nodes

We have found that color coding the wires that belong to each node as shown in Figure 1 has helped students realize that the node is more than just a little dot on a circuit diagram. This also helps emphasize the differences between voltage difference and node voltage. This idea came from consulting with the Center for Persons with Disabilities about students who are dyslexic.

We also use color coding to help students understand elements in series (which have a single color on the ordinary node between them), and parallel (which share two colors). If a short circuit is added, and the nodes are colored accordingly, elements that are shorted out will have the same color on both sides.

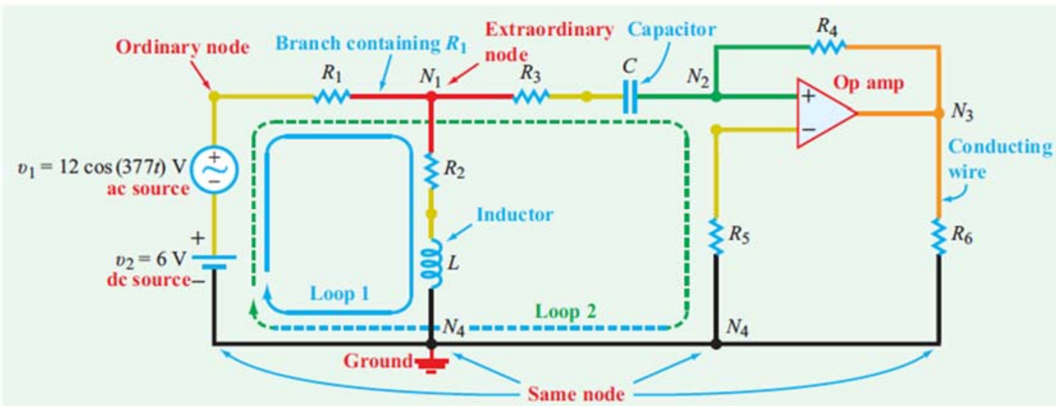



Figure 1 Color coding the nodes. From [4].

### B. Circuit analysis toolbox

One of the major challenges students have in their first circuits class is figuring out what method to use to solve a particular problem. Students often feel they are swimming in a sea of equations, and that every problem is unique with little or no relationship to others they have solved. To address this challenge, we created a circuit analysis toolbox, shown in Figure 2. Each section of the toolbox shows the input and output variables for each method. The sections can be cut into cards (many students glue these to 3x5 cards). Then, the cards can be arranged to plan out the method to solve a particular problem, matching up the input and output variables for each method, somewhat like dominos.

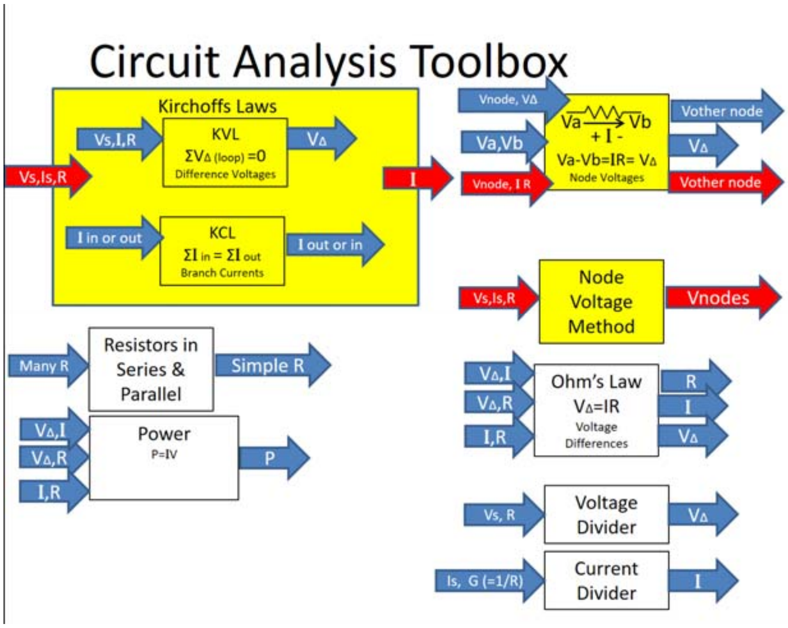
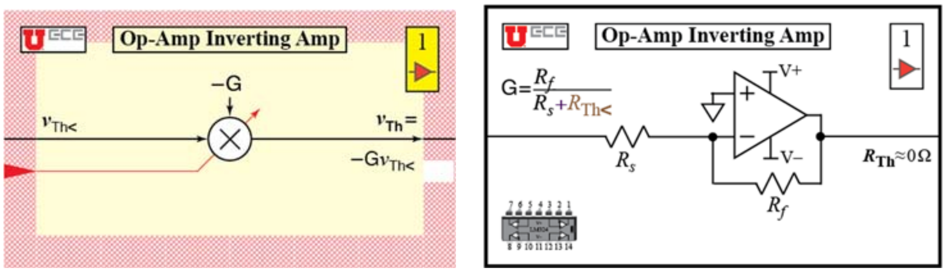


Figure 2 Circuit analysis toolbox. Each block describes input and output variables for each method. These can be cut into cards and laid end-to-end to represent the method to solving a circuit. If you want to find voltage across a resistor, for instance, you could use KVL/KCL to find current and then Ohm's law to find the voltage.

### C. Circuit system design cards

Another major challenge that we have addressed in our class is system level design thinking. The students create an invention of their own as a final project in the lab. An example might be a "Cocoa-controller" that measures the temperature of cocoa and turns on the "heat" (a red LED) if it is too cold or a fan if it is too hot. This uses a thermistor, op amp comparator, two level shifters (multiply/divide, add/subtract), an output LED and small motor with a paper fan. The first year we tried this, students particularly struggled with the concepts of designing the system, particularly how to get started. Gradually, we have added several system design concepts to the course and to the textbook. Perhaps the most useful of these is a deck of Circuit System Design (CSD) cards [1].

The concept for a deck of Circuit System Design Cards is shown in Figure 3. The system design of the card (on the left) shows the function of the card, what it "does" to a voltage. This card multiplies the voltage by a value -G. The back side of the card (on the right) shows the circuit. Students design the system by first laying out the cards with the system side up. Then they flip the cards over to the circuit side and design the details of the circuits to implement the system. When working with the students in class, it became apparent that the value of the cards was not so much in the understanding of the circuit – they more or less had that figured out pretty well. Rather, using the cards as manipulatives helped change their thinking to deliberately consider the system first.




(a) (b)

Figure 3 Inverting op amp amplifier card. (a) System side, (b) Circuit side.

The cards also include formulas showing how the output voltage and resistance (basically the Thévenin equivalent of the system) evolve as signals are passed from left to right. This approach teaches system design thinking, as well as the details of each circuit. It also provides more practice and experience with Thévenin equivalent circuits, another topic students initially struggle with. Details are given in [8], and a list of cards is given in Table 3. Files that can be printed out to create these decks of cards are available upon request.

Table 3: List of Circuit System Design (CSD) cards

| | | |
|---|---|---|
| Voltage source<br>Voltage reference<br>Resistors (series, parallel)<br>Op amp inverting amp | Op amp non-inverting amp<br>Op amp buffer (V-follower)<br>Op amp (inv) summing amp<br>Op amp non-inverting summer | Op amp differential amp<br>Op amp level shifter<br>Comparator<br>LEDs |

**D. In class demonstrations**

Many engineering students are hands on learners who benefit from seeing actual circuits. Demos show the practical aspects of building circuits, what components look like, and how measurements are made. A working demo proves that circuits can be successfully designed and constructed and that concepts introduced in class are valid. They also reveal the discrepancies between theory and practice.

We constructed compact demos (8.5" x 11" x 1") on small breadboards as shown in Figure 4. These may be plugged together sequentially to build a system. A document camera used above the circuit can be used to share it with the class.

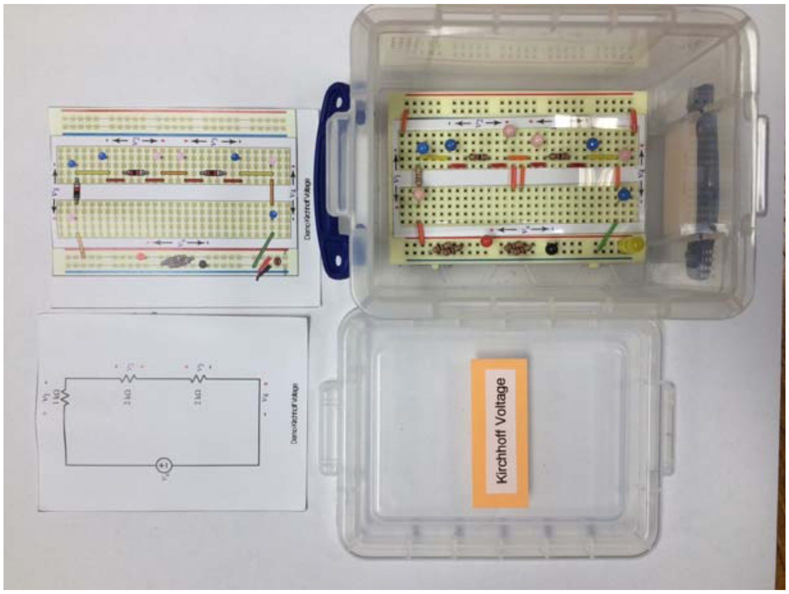


Figure 4: Demo kit for Kirchoff's voltage. Similar kits exist for a variety of topics.

Demos are built on small breadboards (available from Radio Shack [11]). Cellphone chargers made by Mophie [12] provide a regulated, isolated, short-circuit protected 5V at high amperage. Modified USB cables connect the cellphone charges to the breadboard. 5V LED's (from Digi-Key [13]) indicate the presence of power. A list of demos is given in Table 4. These designs can be shared upon request.

Table 4: List of demos

| Unit 1 | Unit 2 | Unit 3 | Unit 4 |
|---|---|---|---|
| Basic circuit | Node voltage | Voltage source | RC circuit |
| Circuit elements | Superposition | Voltage reference | Series capacitors |
| Kirchhoff's voltage law | Thévenin equivalent | Inverting amplifier | RL circuit |
| Kirchhoff's current law | D to A converter | Non-inverting amp | Series inductors |
| Measure v, i for R | Max power transfer | Buffer (V-follower) | Sinusoidal signal |
| Measure v, i for LED | | Summing amp | Phasors and impedance |
| Series resistors | | Non-inverting summer | |
| Parallel resistors | | Differential amp | |
| Voltage divider | | Op amp | |
| Current divider | | Level shifter | |
| Wheatstone bridge | | Comparator | |

## IV. Conclusions

Final course grades were investigated to evaluate the impact of the changes made in the course. End of semester grades over several semesters, taught by three different instructors is shown in Table 5. Note that in addition to differences between teaching styles of the instructors, there are measureable class size and demographic differences between the semesters (more retake students in summer, for instance). This makes it impossible to compare across professors, but this data does give an indication of variation across semesters. Grades of B-, B, or B+ were considered to be in the B range, and similarly for each grade range. Grades of A,B,C were considered passing. D's and F's were considered failing grades.

Table 5: End of semester grade information.

| Instructor | 1 | 1 | 1 | 1 | 1 | 1&2 | 2 | 2 | 2 | 3 | 3 | 3 | 3 | 1&3 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | '13 | '14 | '15 | '16 | '17 | '14 | '15 | '16 | '17 | '13 | '14 | '15 | '16 | '17 |
| # students | 130 | 54 | 59 | 74 | 64 | 119 | 78 | 80 | 83 | 42 | 24 | 20 | 18 | 20 |
| % A grades | 30% | 32% | 39% | 38% | 30% | 24% | 46% | 45% | 42% | 35% | 60% | 44% | 50% | 26% |
| % B grades | 37% | 27% | 29% | 27% | 25% | 30% | 24% | 23% | 32% | 35% | 10% | 19% | 39% | 32% |
| % C grades | 15% | 7% | 8% | 13% | 11% | 14% | 6% | 16% | 11% | 13% | 5% | 19% | 6% | 26% |
| % passed | 82% | 66% | 76% | 78% | 65% | 69% | 76% | 84% | 84% | 83% | 75% | 81% | 94% | 84% |
| % failed | 18% | 34% | 25% | 22% | 35% | 31% | 24% | 16% | 16% | 18% | 25% | 19% | 6% | 16% |
| Withdrew | 18 | 19 | 17 | 15 | 9 | 3 | 10 | 6 | 5 | 2 | 17 | 20 | 0 | 0 |
| Incomplete | 0 | 0 | 0 | 0 | 2 | 0 | 0 | 0 | 4 | 2 | 0 | 0 | 0 | 0 |
| Flipped | N | N | Y | Y | Y | Y | Y | Y | Y | N | Y | Y | Y | Y |

It is interesting to observe the increase in grades as changes were implemented in the course. Table 6 shows the dates the changes were first made and the learning tools implemented. After a learning tool was implemented, improvement with that tool is also noted.

Table 6: Implementation schedule for learning tools

| Semester | Learning Tools |
|---|---|
| Spring 2014 | Flipped class, Real-world examples, Laboratory redesign (improved continuously in following semesters), Step-by-step cookbooks, Color the nodes, Circuit System Design cards (basic), Circuit analysis toolbox (rough), Online feedback |
| Fall 2015 | Circuit System Design cards (improved) |
| Spring 2015 | Circuit analysis toolbox (improved) |
| Summer 2015 | In class demos |
| Fall 2016 | In class demos (improved) |
| Spring 2016 | Circuit analysis toolbox (improved), Muddiest Point feedback |
| Spring 2017 | Question cards in class |

Broad variation is seen from semester to semester. Two professors (teaching in spring and summer semesters) have seen a consistent increase in the pass rate of the class, and one has seen mixed results. The spring and summer increases in pass rate are particularly interesting, as these come from both the largest (83) and smallest (18) enrollment semesters, respectively. Throughout the period of changes, all three professors had access to all previous exams for the course (from all professors), and attempted to maintain consistency between the exams. It is impossible to tease out the effect of each individual teaching improvement from these end-of-semester grades. However, since we have been teaching the course in a flipped fashion, the in class interactions with the students give us immediate feedback on the understanding and/or confusion of the class. We have had to rely on this more qualitative formative assessment to evaluate the various teaching methods discussed in this paper, and to improve them from year to year. The summative end of semester grades indicate that the collective improvements have paid off with a general improvement in pass rate for the course.

This paper describes common challenges in a first circuits course taught flipped. The challenges are both with the content of the course and with learning issues outside of the class content. We have described a number of methods for addressing these challenges including circuit system design cards, demos, cookbooks, circuit analysis toolbox. The CSD cards specifically address Thévenin equivalents and hands-on manipulative; demos help hands-on learners and demonstrate lab techniques; cookbooks assist with sequential thinking and solving large systems; circuit analysis toolbox indicates which analysis tool to apply to circuit solution. The combination of these methods helped improve final course grades.

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