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BYOE: Circuit Modules for Visualizing Abstract Concepts in Introductory Electrical Engineering Courses

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Presenter Information:

The author welcomes the opportunity to collaborate on the development of courseware related to undergraduate laboratories for electrical and computer engineering. Design files and printed circuit fabrication for these experimental setups are open-source and available from the author.

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Background

By its very nature, electrical engineering is largely an abstract discipline. While we can easily see the effects of an electrical process, i.e., a light comes on, or a motor turns, the underlying principles of the process are frequently only understood via mathematical expressions. This may lead to incomplete student comprehension or a level of discomfort with the material. Many undergraduate courses such as Circuits or Electronics include a laboratory component that attempts to alleviate this condition and frequently simple concepts such as Ohm's law, power consumption, or basic filters, are adequately exemplified. However other concepts such as phasor addition of voltages and superposition, fixed current sources, and controlled current sources, are not covered in a self-contained laboratory context. A survey of typical undergraduate programs in electrical engineering reveals that while these topics may be covered in a limited context as part of larger experiments, they are not included in stand-alone experiments in spite of the high level of sophistication of the equipment available to the students [1],[2].

In this paper, we present three simple modules that can snap into a typical solderless breadboard and allow students to visualize and experiment with fixed current sources, controlled current sources, and phasor/superposition experiments.

Pedagogical Context

Beginning in the Fall of 2014 we instituted a major curriculum update in Electrical and Computer Engineering at the University of Virginia. Our basic three-course sequence of "*Circuits*," "*Electronics*," and "*Signals and Systems*" was replaced by a new sequence, "*Fundamentals 1*,*2*, and *3*". Our approach focuses on a learning studio technique with highly integrated laboratory and lecture components [3],[4]. In each successive course, many of the same topics are covered, and at an increasing depth of understanding. This approach has been shown to increase learning of complex topics while minimizing the cognitive load at each phase [5].

A substantial portion of this approach is a tightly integrated lecture-laboratory approach, i.e., a learning studio; our environment is shown in Figure 1. Our studio space creates an open and collaborative “feel,” while still maintaining audio-visual equipment for instructor presentations, and a full suite of laboratory test equipment for experiments via the National Instruments *VirtualBench* [6].

Figure 1 Studio Environment

We have found the studio approach to create a highly effective learning environment, but it requires the ability to set up quickly and tear down experiments. This provided a strong motivation to develop small self-contained experiments that would clearly and quickly convey fundamental concepts. In the balance of this paper, we discuss three devices that enable us to do this – a fixed current source, a phase shifting voltage source, and a controlled current source. Each is very small and adapts to a variety of different experimental scenarios.

Fixed Current Source Design

Consider the circuit of Figure 2. It is commonly employed to introduce concepts such as nodal analysis, Kirchhoff's Laws, superposition, and equivalent circuits [7]. The circuit is presented as a means of explanation, and it indeed allows an instructor to derive all of these relationships effectively, yet no experiment ensues. To produce an associated experiment for a lecture on these topics would require an isolated 2-terminal current source and students might be told that this is an abstraction used for purposes of derivation.

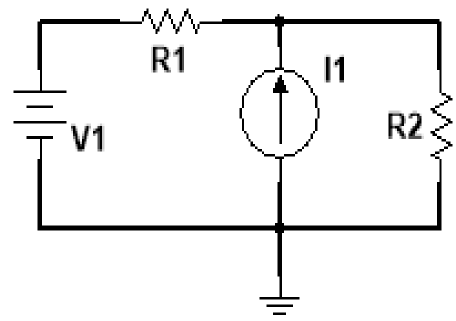

Figure 2 Simple Linear Circuit

We tackled this issue with a simple battery-operated 2 terminal current source shown in Figure 3.

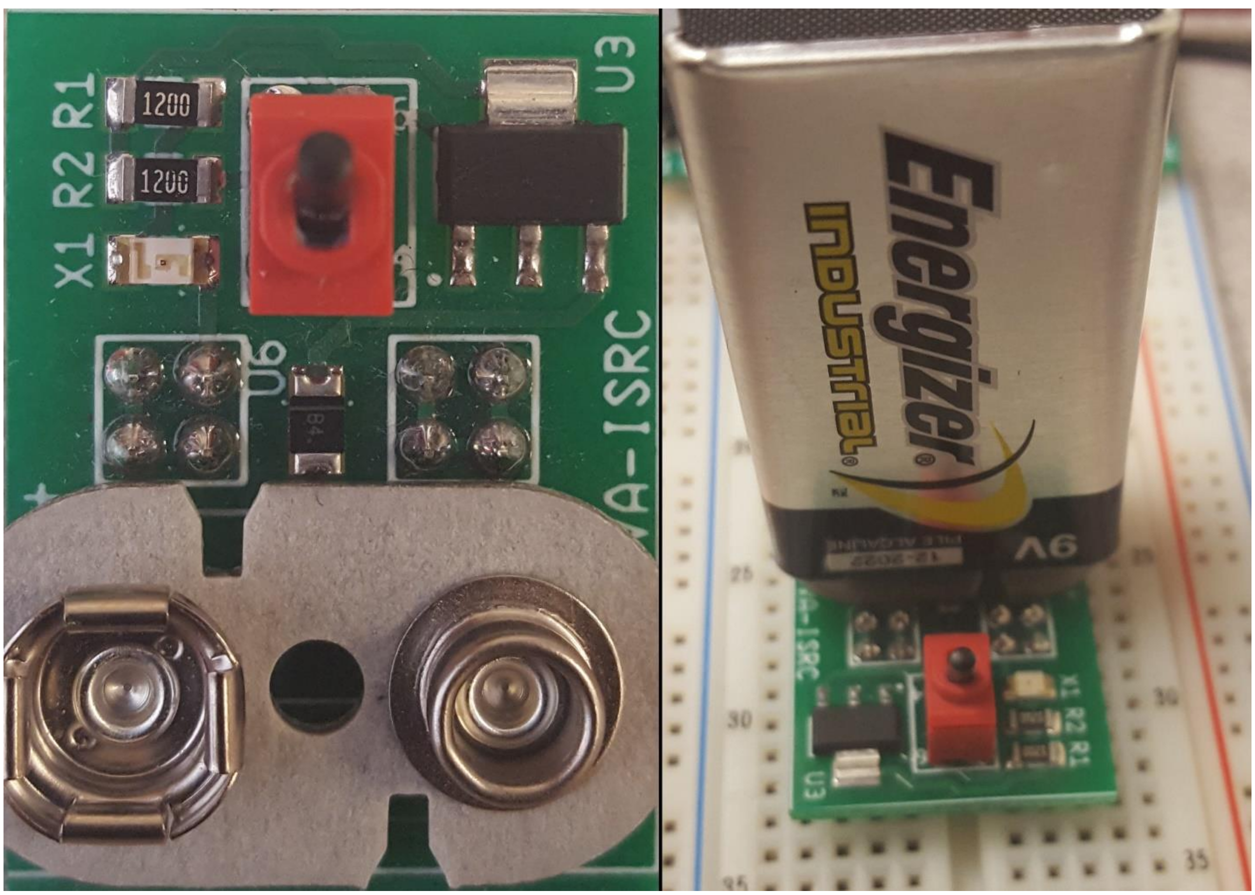

Figure 3 Current Source Views

The device is powered via a 9V battery which clips directly on to the unit, allowing for true floating operation. The switch enables the students to change currents from 10 mA to 20 mA. Also, an LED allows visual confirmation of operation and changes in intensity when the current setting is changed.

The design is rendered with surface mount components for size and space considerations. However, the smallest parts are 1206, which are easily hand-soldered. Also, the pins and spacing are designed such that it readily snaps into a solderless breadboard. In small quantities, the board can be assembled for approximately $22 in parts cost. The small size facilitates adding other parts to experiments with creating undue complexity for the students. Also, the 2-terminal design eliminates battery drain when the device is unplugged from the breadboard.

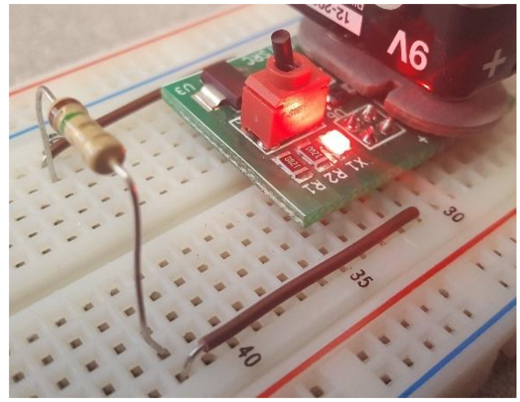

Figure 4 Current Flow Indication

The schematic is shown in Figure 5 below.

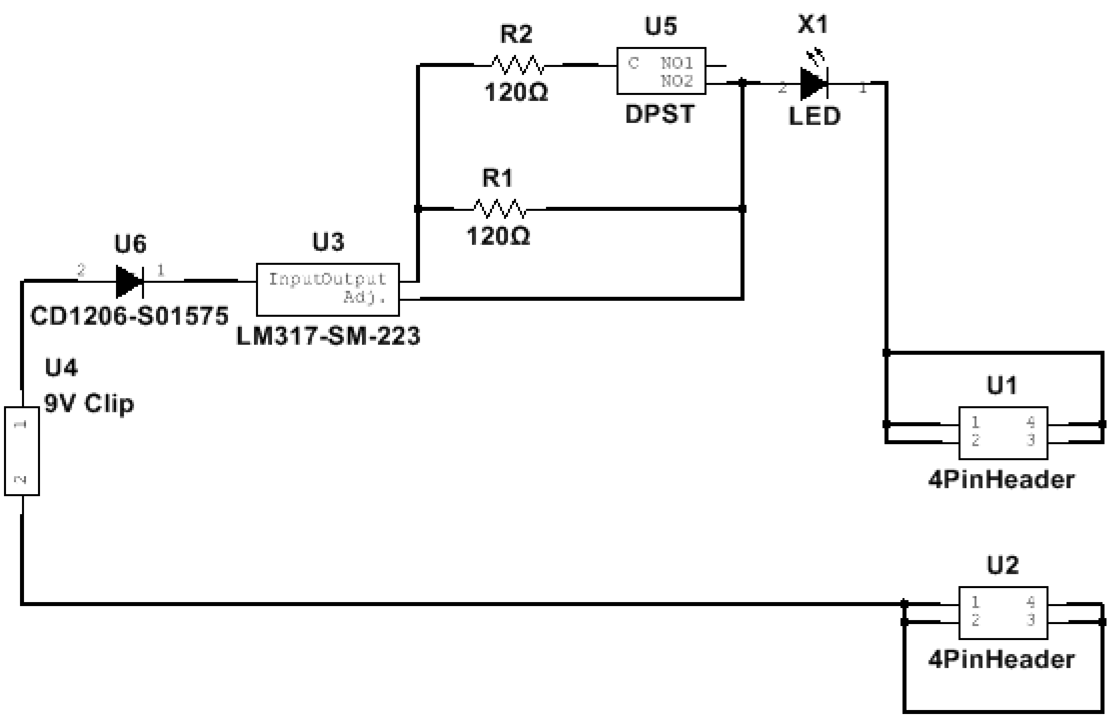

Figure 5 Current Source Schematic

The circuit is not only simple but very robust. It has been used for four semesters without a single failure! The heart of the current control is the LM317 voltage regulator [8]. This device may be configured as a current regulator and when used with the battery as shown it constitutes a fully floating 2-terminal current source. The device can withstand an input-output voltage differential of 40 volts, which is well beyond the range of typical power supplies found in an undergraduate electronics laboratory. Diode U6 is used for reverse polarity protection, and the switch engages two different resistor combinations to set the current for either 10 or 20 mA. The LED indicates that the circuit is active, and is noticeably brighter at the 20 mA setting, providing visual feedback for the students.

Current Source Classwork

A typical assignment for which we employ the current source is shown in Figure 6 below. The students are presented with a lecture on linearity and superposition and then asked to solve the circuit shown. The assignment asks them to consider three approaches. First, they develop an analytical solution employing superposition techniques. Next, they create a simulation to verify the results of their analysis using *Multisim* [9]. Finally, they build and verify the circuit operation using the current source. As part of the experiment, they are asked to use an ammeter to measure the actual current delivered by the current source, and we consider this portion of the exercise to be an excellent exposure to verifying component operation and dealing with manufacturing tolerances.

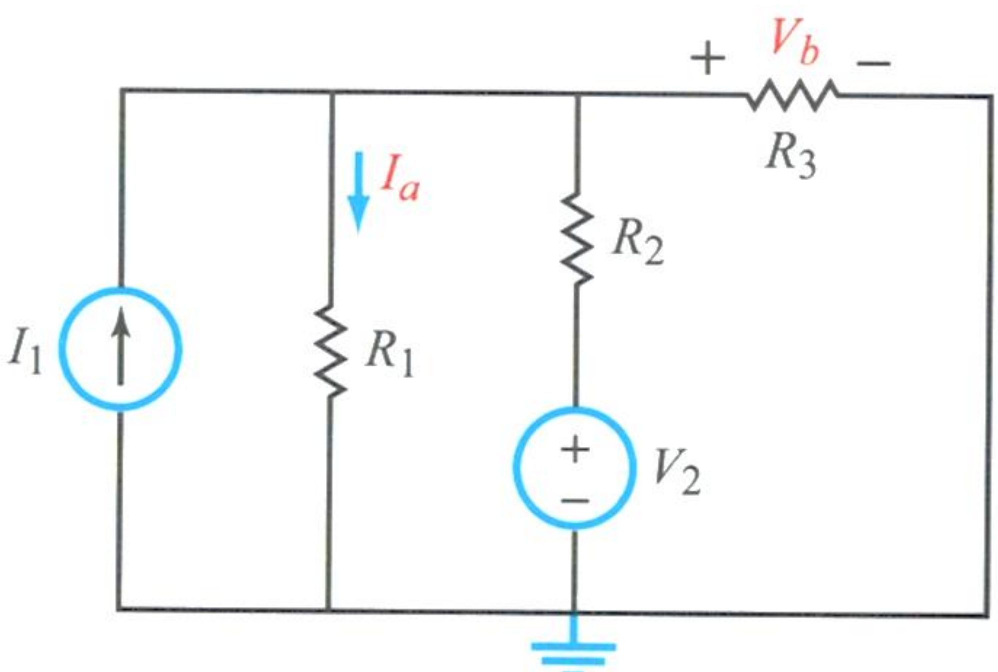

Figure 1

For the circuit shown in Figure 1, use superposition to develop an analytical solution for the voltage, V_b , for $I_1 = 10$ mA, $V_2 = 3$ V, $R_1 = 100\ \Omega$, $R_2 = 220\ \Omega$, $R_3 = 470\ \Omega$. Then, verify your solution numerically. Finally, build an experimental prototype and verify your analytical and numerical solutions.

Figure 6 Typical Current Source Assignment

Assessment of Current Source Learning Outcomes

This device has been employed by several different instructors in our *Fundamentals 1* introductory course. Feedback from students has been universally positive when quizzed about the efficacy of the device as an aid in understanding both current source operation as well as principles of superposition. Each instructor has also provided very positive feedback regarding its utility in explaining these important concepts, and allow a topic, i.e., current sources, that was once relegated to purely mathematical abstraction, to be used in actual laboratory experiments.

Phase Shifting Voltage Source Design

Our second module is a phase-shifting voltage source for experiments with phasor addition of voltages. Again, our survey indicated that although phasor experiments are virtually a staple of undergraduate laboratory exercises in electrical engineering, the approach employed is in the design and analysis of filter circuits. A missing element is the laboratory experience of the voltage addition of phasors. Before introducing this experiment to our *Fundamentals* coursework, students at the University of Virginia would never see this concept without taking our course in *Electromagnetic Energy Conversion* in which they would deal with polyphase systems. We also realized that having a lab bench accessory that would produce phase-shifted sinusoids could be employed as a teaching tool for reinforcing concepts in superposition and operational amplifier circuits, as well as phasor analysis.

Our design is shown in Figure 7. Note that it is also a very compact design and that the pins mate with the solderless breadboard such that power and ground are automatically distributed to the board.

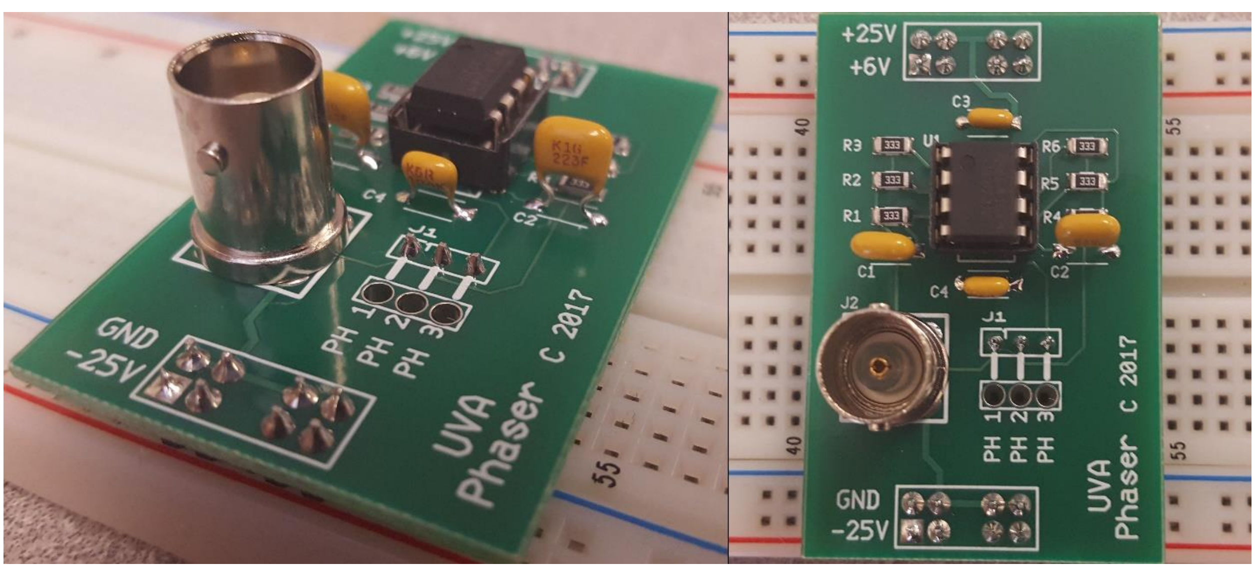

Figure 7 Phase Shifted Voltage Source

A typical classroom setting is shown in Figure 8 below. The compact nature of the device facilitates uncluttered laboratory setups and allows students to study concepts such as phasor addition of voltages and superposition for alternating current signals.

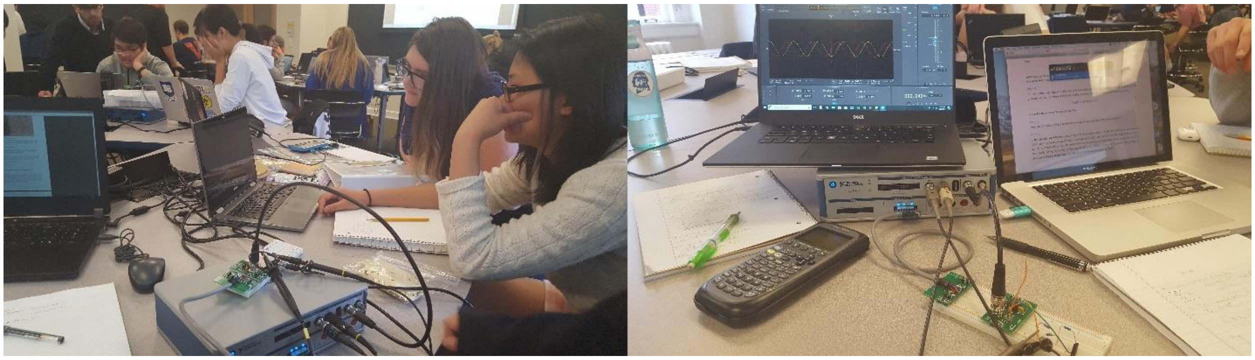

Figure 8 Phase Shifted Voltage Source in Class

The schematic is shown in Figure 9 below. It is implemented as an all-pass filter. A characteristic of this type of filter is that the output magnitude is a constant, and the phase shifts as a function of frequency. We provide two cascaded outputs and the input as passed through as an additional output. This configuration allows us to provide a total of 3 outputs and the phase of the third output is twice that of the second, i.e., if the input is at 0 degrees, then the first output might be at 60 degrees, and the second at 120 degrees.

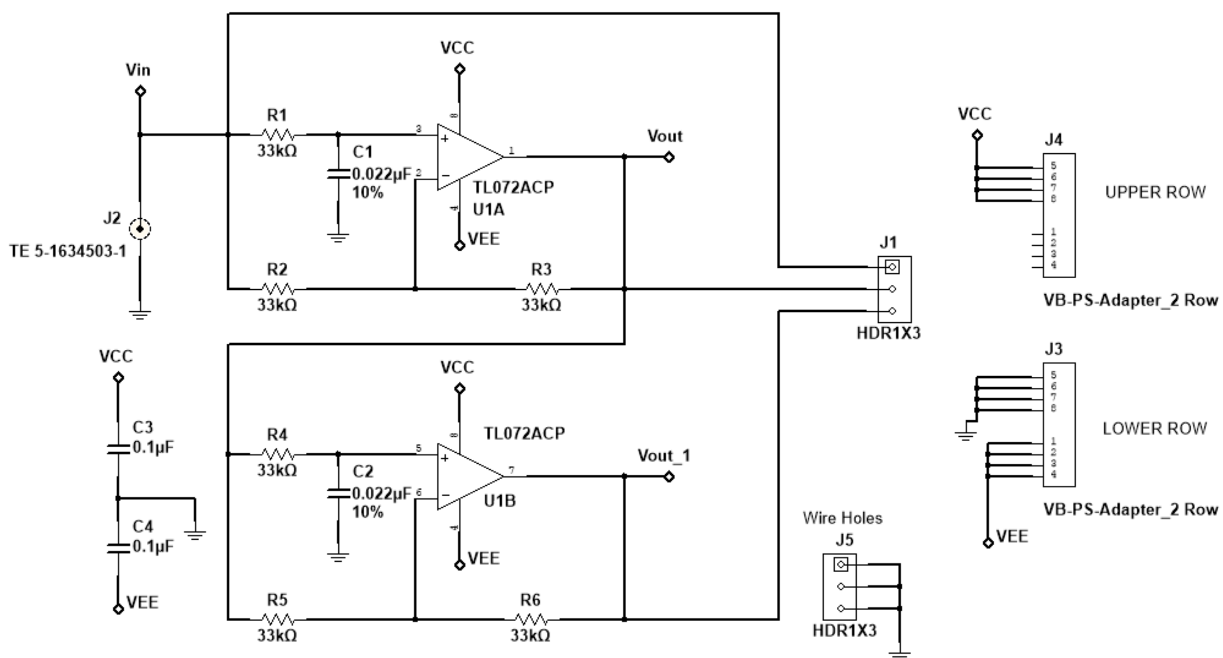

Figure 9 Phase Shifter Schematic

The circuit is implemented as two identical sections and employs a dual operational amplifier, the TL072 [10]. This is a very commonly used device and is also the one used by our students in their laboratory part kits. It has excellent performance and yet remains very modest in cost. Total build cost for this board is approximately $16 in parts in low quantities. The resistors are 0.1% tolerance, and the capacitor is 10%. With these components, we have seen excellent unit-to-unit repeatability in performance. They are also extremely rugged, having been used in class for two semesters with no failures. The resistors are the only components in surface mount, but they are of 0805 size format and still very easy to solder by hand.

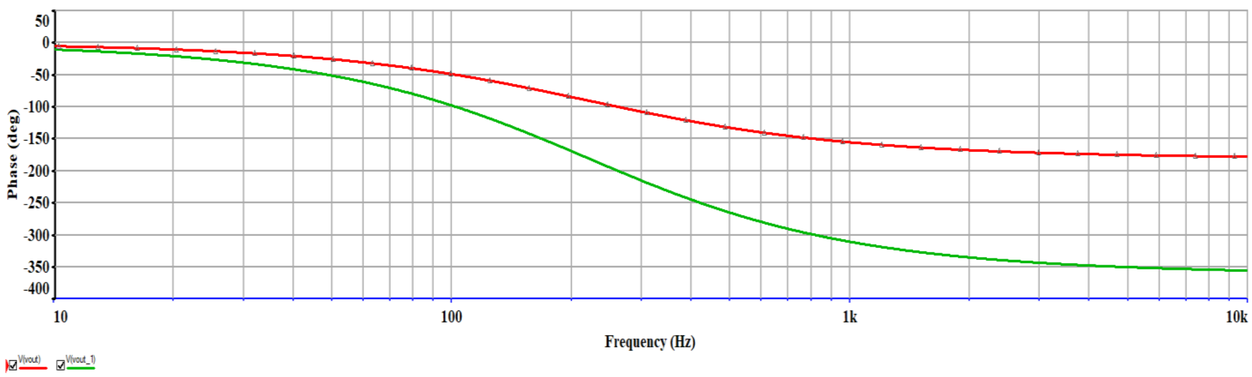

Figure 10 Phase Characteristics

The phase shift curves are shown in Figure 10. Note that the first output is not shown; it is simply the input passed through, so there is no phase shift.

Phase Shifting Voltage Source Classwork

This circuit is very flexible and may be employed in several different experiments. For example, we use it in *Fundamentals 2* in an experiment to reinforce both phasor voltage addition as well as superposition. Our setup is shown in Figure 11.

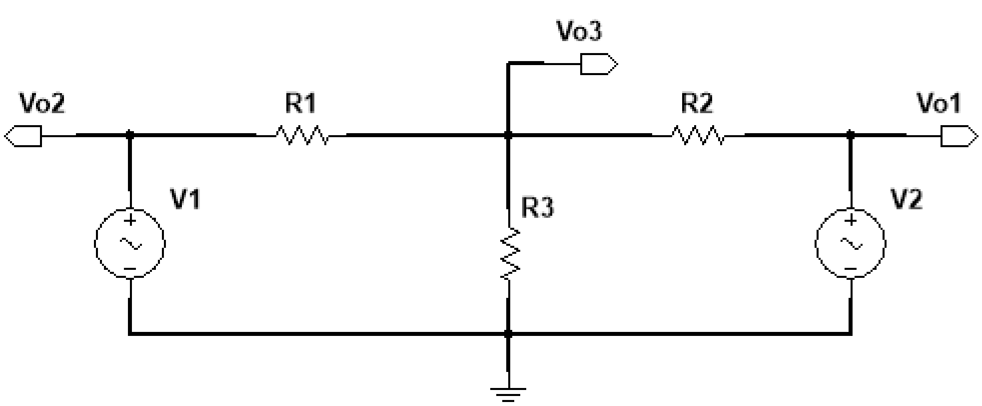

Figure 11 Phasor/Superposition Experiment

In this experiment, we specify a function generator frequency of 220 Hz, which yields a 90-degree phase shift between outputs – the students measure this as it is not given. We then have students measure *Vo3* with *Vo1* being supplied with the unshifted pass-through signal and *Vo2* receiving the phase shifted version. The students perform the measurements with each source separately, while the other input is shorted to ground; the respective unused channel is disconnected. As a lab exercise, the students then perform the superposition calculations and verify that the calculated result agrees with that measured when both sources are connected. This procedure gives practice with phase measurements, phasor calculations, and superposition using only three resistors in addition to the source.

Assessment of Phase Shifting Voltage Source Learning Outcomes

Students were assessed on their understanding of phasors and superposition via laboratory write-ups at the conclusion of their experiments. Results were:

A. *"Perfect Understanding":* Students were able to perform precise measurements of voltage amplitudes and phases, compare to theoretical results, and thoroughly explain, through mathematical analysis, their results. – 50%
B. *"Excellent Understanding":* Students were able to perform precise measurements of voltage amplitudes and phases, compare to theoretical results, and offer some mathematical analysis. – 13%
C. *"Good Understanding":* Students were able to perform precise measurements of voltage amplitudes and phases. However, comparison to theoretical results was incomplete. – 25%
D. *"Some Understanding":* Students were able to complete some measurements, but results may have been imprecise, or there was no comparison to theoretical results. – 12%

An advantage to using a preassembled module for this experiment is that we do not give the students the schematic of what is on the board or describe how it works, i.e., it is treated as a black box, and the students do not have access to it outside of class periods. By taking this approach, we can present the circuit later in the semester as a homework problem. The all-pass filter is obscure enough that the students are not likely to have seen it in the past. In this scenario, the students are simply given the circuit schematic with no functional description and asked to derive the transfer function. The faculty or teaching assistants are instructed not to answer any questions on this homework; the students are instructed to think of it as a self-evaluation of their progress so far, although it is a graded assignment. Under these conditions, students achieved an average of 92% on this problem.

We are envisioning further uses for this board. One example is to set the frequency such that 120 degrees of phase shift is achieved at each output and have the students experiment with 3-phase concepts at low voltages. Another possibility is to explore audio effects derived from phase shifting inputs.

Voltage Controlled Current Source

Our third (and most ambitious) circuit module is a voltage controlled current source (VCCS). We have observed that students are uncomfortable with the concept of controlled sources, especially current sources, compounding their difficulty in understanding devices such as BJT's and MOSFET's where input currents, threshold voltages, and diode voltage drops must also be considered. In the design of this module several goals were our priority:

- The circuit should function without offsets and require negligible input current.
- The circuit should be able to sink or source current over as much of the supply range as possible.
- The current outputs should "float," i.e., either or both outputs should function at voltage levels that do not require one or the other to be tied to ground or a power supply voltage.
- There should be a true differential input structure.
- The transconductance of the device should be determined by only one resistor, and precision matched components should not be required. The circuit should be able to accommodate currents up to 100 mA with no change in components other than that resistor, assuming that dissipation limits are observed.
- The circuit should comply with the form factor of our phase shifted voltage source such that it will snap onto a solderless breadboard and extract all needed power voltages from the existing rail voltages.
- In summary: the circuit should function as much like as an ideal voltage controlled current source as possible.

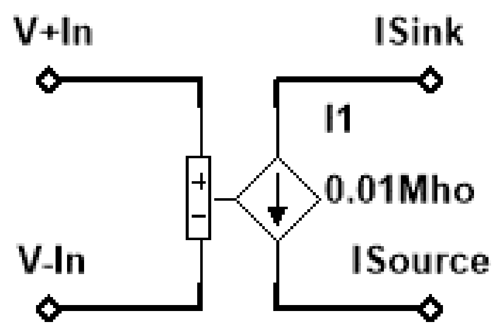

Figure 12 VCCS Schematic Symbol

The conceptual symbol for a VCCS is shown in Figure 12. Our device is currently configured for a transconductance of 10 mA/Volt. The corresponding connections for the module are shown in Figure 13. Note that all power supply connections are made through the solderless breadboard when the device is loaded such that the students need only wire the inputs and outputs to have a fully functional VCCS on their laboratory setup. Also, note that the circuit is equipped with test points enabling observability at key nodes for later experiments where students will be asked again to find the transfer function of the circuit and evaluate the functions of the interior nodes; the schematic of the module is not presented at this point in the laboratory sequence.

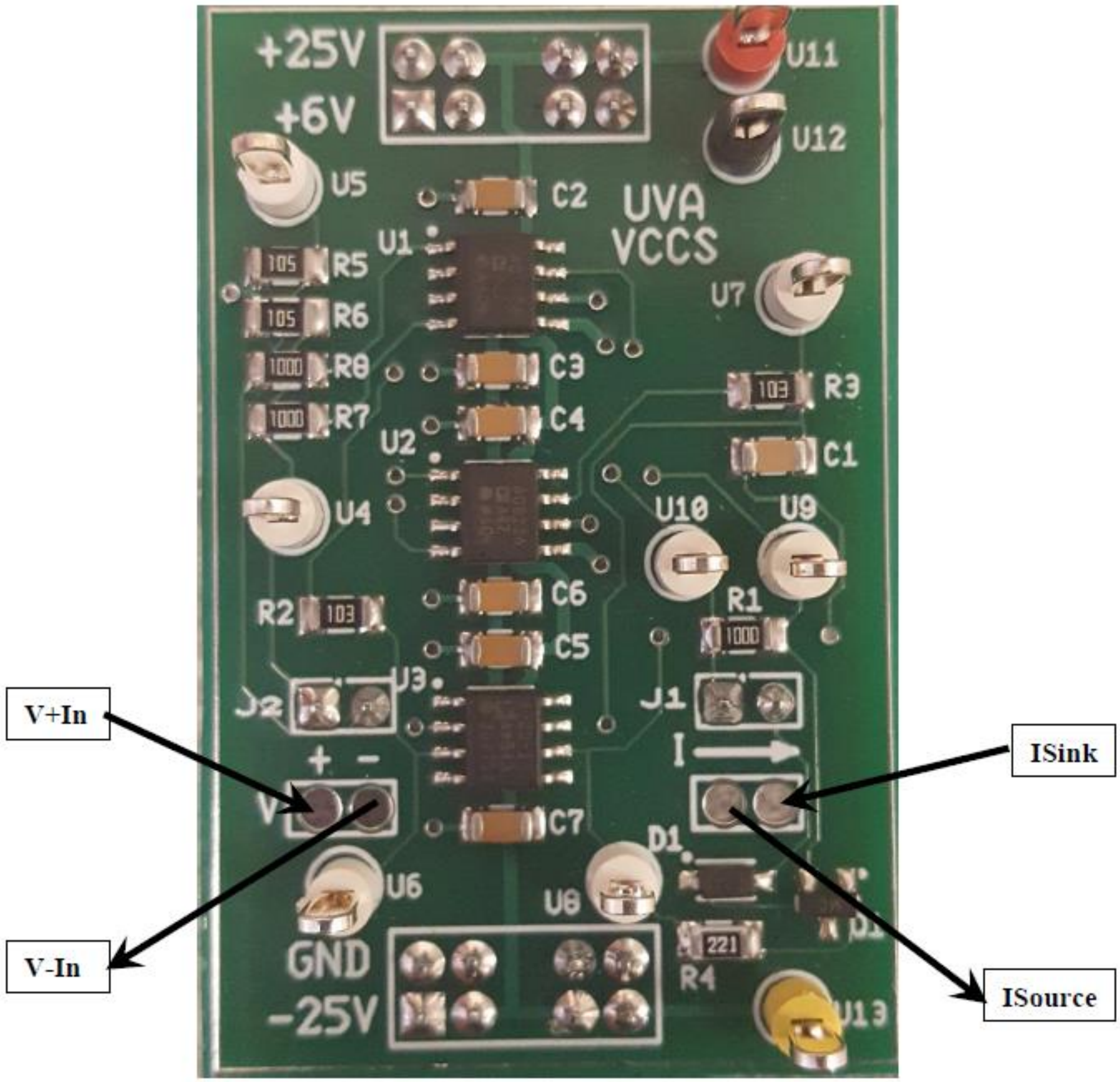

Figure 13 VCCS Module

The overall schematic is shown in Figure 14 below. U1, the AD8226, and the associated components function as a precision difference amplifier with unity gain [11]. Resistors R7 and R8 provide a measure of input protection and isolation for the circuit. This amplifier can operate correctly if the inputs are at any range within the power supply voltages satisfying our design criteria for the inputs. U3, the ADA4000 functions as an integrating error amplifier and drives the gate of the ZVN3306 N Channel MOSFET which is the output device [12]. The MOSFET is protected from reverse voltages by D1, a 1N4148 diode and is capable of supplying 100 mA satisfying a design requirement. Feedback is taken from R1, the current sensing element, and is amplified by U2, a second AD2226. This arrangement also enables the output to go completely to the range of the power supply rails, satisfying our criteria for the output range. R1 is the only circuit element that determines the overall transconductance, further satisfying our design requirements. This circuit can be assembled for approximately $28 in parts and the surface mount components are large enough to be mounted by hand with little trouble. Extensive testing has shown that the circuit has excellent performance and the expected currents are well within 1% of the measured ones.

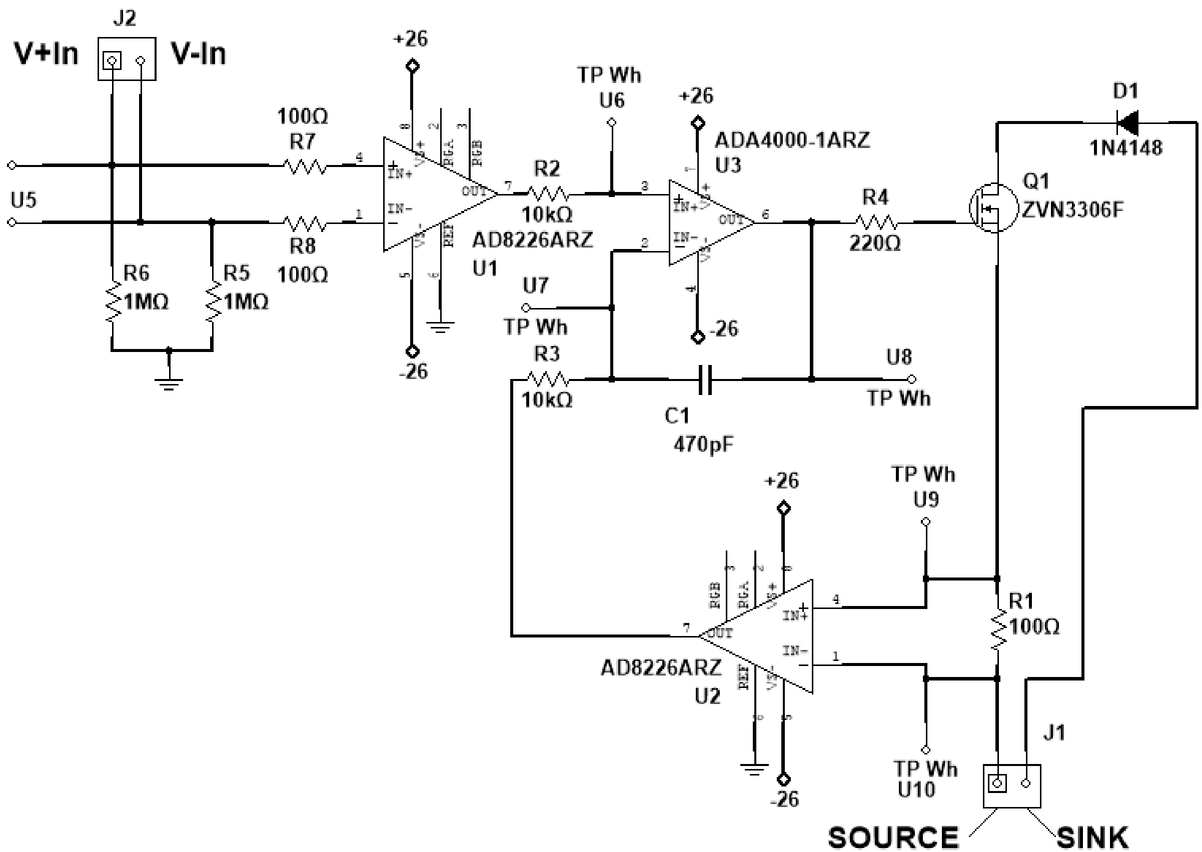

Figure 14 VCCS Schematic

VCCS Class Work

This module is used in a preparatory session for upcoming work with BJT's. The students are given a brief explanation of voltage controlled current sources with reference to Figure 12. There is an emphasis on the concept that the current driven from the sink to the source pins is a function of the difference between the voltages at *V+In* and *V-In*. Also emphasized is the concept that the current is determined by the transconductance as well and that its units are *Amperes/Volt.* Armed with this brief lecture, the students are then presented with the circuit module, and the functions are related to the schematic symbol as shown in Figure 12. The experimental setups are shown in Figure 15.

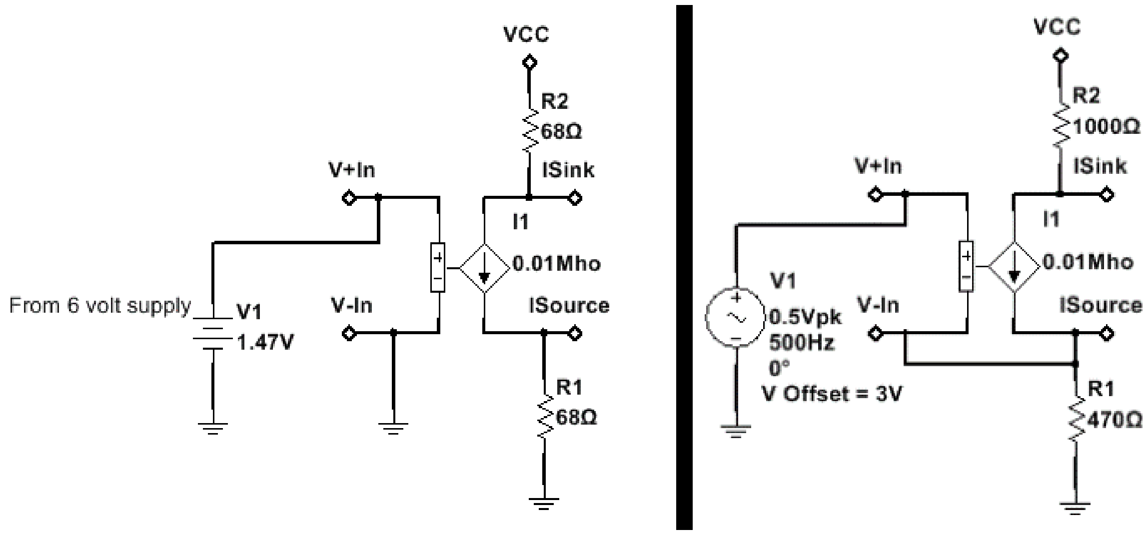

Figure 15 VCC Basic Laboratory Experiments

In the circuit on the left, students are asked to verify that the current leaving the *ISource* pin is identical that entering the *ISink* pin and that it varies as a linear function of the voltage applied to *V+In* pin with the *V-In* pin grounded. Various resistor combinations are also used to show that the output is indeed a current and that changing a resistor such as R1 or R2 does indeed change both the voltage across the resistor as well as the voltage from *ISink* to *ISource*. Theoretical calculations are performed in the lab as the experiment proceeds, and the students compare measured results and theoretical predictions. A general biasing equation is then derived for the circuit on the right, and theoretical and measured results are again compared. Students also apply A.C. signals to the device and measure gain as well.

Assessment of Controlled Current Source Learning Outcomes

At the conclusion of the experiment, a brief quiz on controlled source operation was given. As this experiment is intended as a brief refresher for controlled sources immediately before a lengthier experimental sequence on bipolar junction transistors, the quiz is necessarily short and intended to focus on basic concepts. It was constructed as a True-False quiz with the following questions:

- *"In a voltage controlled current source, the current that flows through the source is a function of the voltage at Vin+ only. In a voltage controlled current source, the current that flows through the source is a function of the voltage at Vin+ only*." The correct response to this question was 93.5% While an excellent result, it did indicate some confusion about the function of the control terminals and provided a launchpad for class discussion on the topic.

- *“The current that flows into the "sink" terminal will be equal to the current that flows out of the "source" terminal.”* The score on this question was 100% indicating that there was a strong understanding of the implications of Kirchhoff’s Laws.

Students were also polled on the usefulness of the experiment in helping them understand the concept of controlled sources. 58% agreed, and 29% strongly agreed that it helped solidify their understanding of controlled sources.

Also, the experimental write-ups were assessed for understanding of controlled source operation. The results were:

A. *“Perfect Understanding”:* Students were able to precisely measure and numerically compute the expected results, compare to simulations, and explain the relation to Bipolar Junction Circuits. – 22%
B. *“Excellent Understanding”:* Students were able to precisely measure and numerically compute the expected results with some explanation of operation and comparison to simulations. – 22%
C. *“Good Understanding”:* Students were able to precisely measure and numerically compute the expected results. Explanations and comparisons were attempted but not thorough. – 22%
D. *“Some Understanding”:* Students were able to measure and numerically compute the expected results, but explanations and comparisons were weak. – 33%

The assessment of laboratory reports required both numerical calculations as well as explanations and conclusions. We view these assessments as a valuable tool in measuring both student retention of concepts as well as guiding successive class offerings.

Summary and Conclusions

We have designed and deployed three small circuit modules that may be readily employed in undergraduate electrical engineering teaching laboratories. The modules are designed to allow experimentation with fundamental concepts that are usually taught as abstractions and have no direct experiential component.

In the past, we have observed that current sources are a troublesome topic for undergraduates, and we believe that condition is exacerbated because most of the measurements students make in a typical laboratory are voltage related. Student testing and experimentation with actual devices improve their understanding of this; we have confirmed this with both formally with test results and polls, and informally with student comments.

Our phase-shifting voltage source allows students to experiment with phasors and superposition in ways that were difficult, if not impossible with conventional laboratory equipment alone. This circuit also enables students to delve into topics previously uncovered in undergraduate laboratories, i.e., polyphase systems.

Small self-contained circuits such as the ones described in this paper allow us to explore these fundamental topics in a manner that includes an experiential component and experience has shown that this is an important factor in solidifying these concepts before moving on to more advanced topics. We welcome collaboration with other institutions to develop more of these simple modules.

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