Turning Laboratory "Failures" into Student Success

***L. Brent Jenkins*[1]**

Abstract – Sometimes, a student laboratory exercise will fail. Our normal approach to such an event is to work to prevent its occurrence. Students frequently get frustrated when laboratory results differ from their expectations, and instructors may be embarrassed, disappointed, or even panic-stricken by the outcomes.

Laboratory failures can provide excellent learning opportunities for students, however, if they are handled properly. Unexpected laboratory failures can sometimes be capitalized on to seize the teachable moment. Lab exercises can, in fact, be intentionally written to succeed through apparent failure. Results that conform to expectations are not nearly as memorable as surprises that demonstrate something meaningful. Frustration can be replaced by the thrill of discovery and accomplishment. Concepts related to equipment limitations and effective laboratory practice can be demonstrated in memorable ways.

This paper explores the orchestration of intentional laboratory exercise "failures" while providing illustrations based on the author's experience in circuits and electronics labs.

Keywords: laboratory, experiments, circuits, electronics, teaching

DIGITAL MULTIMETER (DMM) MEASUREMENTS OUTSIDE THE MEASUREMENT BANDWIDTH

A common misconception among students is the belief that a digital display always conveys an accurate value. Students frequently think that the opposite of an imprecise analog measurement is an accurate digital measurement, a mindset that often leads them to implicitly trust the accuracy of digital readings. Calibration uncertainties aside, there is more at stake here than the need to clarify the distinction between accuracy and precision—students need to learn that no instrument is deserving of blind trust; equipment limitations should always be considered before an instrument is selected for use.

The finite measurement bandwidth of a DMM provides an excellent means to generate a healthy skepticism about the validity of digital measurements. Figure 1 describes a suitable circuit. Since no frequency-dependent elements are evident, the output voltage of Figure 1 should be independent of frequency. The problem with this reasoning is that it ignores the frequency-selective nature of the circuitry in the DMM.

The following illustration assumes a DMM measurement bandwidth of 7 kHz. Application of the voltage divider rule [Boylestad, 1] to Figure 1 yields the theoretical magnitude of the output voltage:

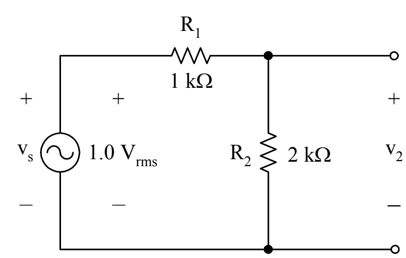

Figure 1: Simple Voltage Divider

$$|v_2| = \left(\frac{2\,\text{k}\Omega}{2\text{k}\Omega + 1\text{k}\Omega}\right)(1.0\ \text{V}_{rms}) = 667\ \text{mV}_{rms}$$

When a 1.0 V_{rms}, 1 kHz sinusoid is applied to the actual circuit, the measured value of $|v_2|$ is 649 mV—sufficiently close to the expected value to be accepted as a "good" result. The quandary arises when the input frequency is changed to 10 kHz—the students expect $|v_2|$ to stay about the same, but instead it falls to 399 mV. The favorable result at 1 kHz serves two purposes—it reinforces the confidence of the students in their construction and

---

[1]Southern Polytechnic State University, Marietta, GA 30060, bjenkins@spsu.edu

measurement abilities, and it provides a basis of comparison for the 10 kHz measurement. The stark contrast perceived by the students when they make this comparison prompts them to ask, "What happened?" This question is the instructor's cue that a teachable moment has arrived.

An examination of the frequency characteristics of the instrument can be used to explain the apparent inconsistency between the two measurements. Figure 2 illustrates why the first reading was so reasonable—at 1 kHz, the DMM is operating at 97.3 % of its calibrated response, so a 667 mV input yields a reading of 0.973 × 667 mV = 649 mV. Figure 3 portrays the situation at 10 kHz—the DMM response is a mere 59.9 % of the actual value, so the same 667 mV input produces a reading of 0.599 × 667 mV = 399 mV. In effect, the DMM is "lying" to the students at 10 kHz because it is being used outside of its normal operating range. Thus, the students are led to the "shocking" realization that digital displays sometimes provide inaccurate readings.

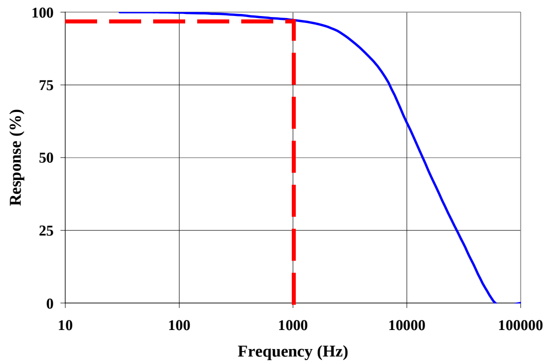

Figure 2: DMM Response at 1 kHz

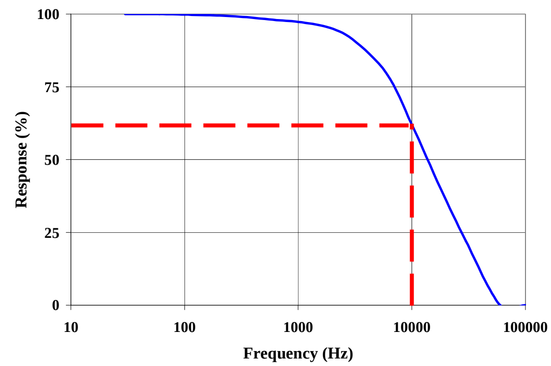

Figure 3: DMM Response at 10 kHz

BACK-TO-BACK MEASUREMENTS IN CIRCUITS WITH DIFFERENT SOURCE LOADING

A second common error among students in the lab is to assume that the amplitude of a function generator is unaffected by the circuit it drives. Students frequently set the function generator amplitude while the instrument is open-circuited, and they fail to readjust this amplitude once the circuit is connected to the instrument. A related error occurs when the student fails to verify the function generator amplitude after a circuit is modified. The following exercise is designed to demonstrate the voltage division principle while reminding students to view function generators as practical voltage sources (i.e., voltage sources that supply their output terminals through a series resistance).

The exercise begins with an analysis of Figure 4. The voltage divider rule yields:

$$|v_2| = \left(\frac{100\,\Omega}{100\,\Omega + 1\text{k}\Omega}\right)(1.0\text{ V}_{\text{rms}}) = 90.9\text{ mV}_{\text{rms}}$$

In this case, the measured output voltage provides a "textbook" result even if the student forgets to readjust the function generator amplitude after the circuit is connected to the instrument.

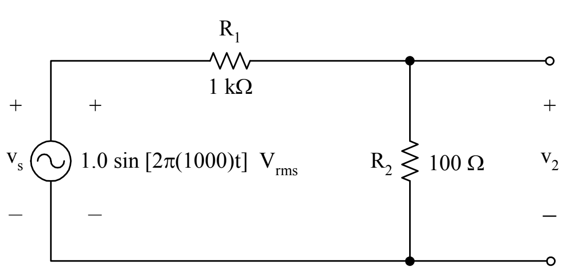

Figure 4: Voltage Divider That Works as Expected

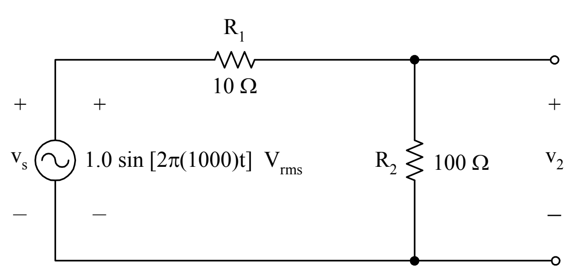

Figure 5: Voltage Divider with Unexpected Results

The exercise continues with an analysis of Figure 5:

$$\left|v_2\right| = \left(\frac{100\,\Omega}{100\,\Omega + 10\Omega}\right)\left(1.0\,V_{rms}\right) = 909\,mV_{rms}$$

The students that remember to readjust the function generator amplitude after the circuit is modified get "textbook" results once again, but the students that forget to do so get about 625 mV. The latter students will invariably seek instructor assistance:

Student: "What am I doing wrong? The circuit has to be right—all I did was replace the 1 kΩ resistor with a 10 Ω."

Instructor: "Are you sure your generator is set to the right amplitude? Why don't you check it to make sure?"

Student: "How did that happen? I know it was right when I started."

What follows is the highlight of the exercise—the instructor adds the source resistance of the function generator to the circuits in the student's copy of the lab exercise, converting them to Figure 6 and Figure 7, respectively. The instructor then notes that while the 50 Ω resistance is negligible in the Figure 6 circuit, it is very important in the Figure 7 circuit.

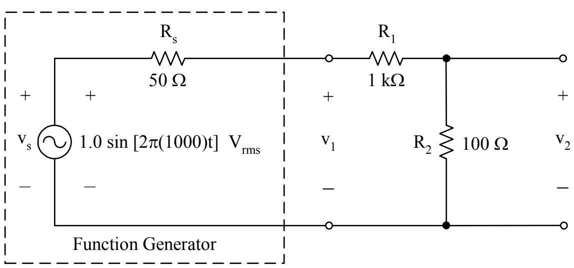

Figure 6: Voltage Divider That Avoids Source Loading

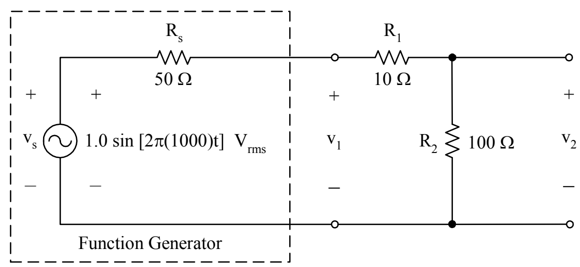

Figure 7: Source-Loaded Voltage Divider

An analysis of Figure 6 yields:

$$\left|v_2\right| = \left(\frac{100\,\Omega}{100\,\Omega + 50\Omega + 1k\Omega}\right)\left(1.0\,V_{rms}\right) = 87.0\,mV_{rms}$$

The 90.9 mV_{rms} result that was obtained using the circuit in Figure 4 compares very favorably to this value. Thus, the source resistance of the function generator plays a minor role in this circuit, and the students that forget to readjust their source amplitude still get good experimental results.

An analysis of Figure 7 yields:

$$\left|v_2\right| = \left(\frac{100\,\Omega}{100\,\Omega + 50\,\Omega + 10\,\Omega}\right)\left(1.0\,V_{rms}\right) = 625\,mV_{rms}$$

This value reveals that the 909 mV_{rms} result that was obtained using the circuit in Figure 5 involved a considerable amount of error. Thus, the source resistance of the function generator plays a significant role in this circuit, and the students that fail to readjust their source amplitude obtain poor experimental results.

Once students are brought to the realization that the terminal voltage of a source decreases as the source current increases, they rarely forget to readjust their source voltage settings in subsequent exercises.

FULL-WAVE RECTIFIER CONSTRUCTION AND MEASUREMENTS

A third error that is frequently made by students in the lab is to confuse *common* and *ground*. A *common* terminal serves as a reference for relative voltage measurements, while a *ground* terminal establishes a basis for absolute measurements. In surveying terms, a voltage referenced to *common* is similar to a height above a shared but arbitrary baseline, while a voltage referenced to *ground* is similar to an elevation above a known reference such as sea level.

An error that is related to this *ground*/*common* confusion occurs when students forget that the *ground* lead of an oscilloscope probe actually grounds the node to which it is connected. This confusion stems from the fact that the black lead of a DMM is <u>not</u> internally connected to *ground* by the instrument; the black lead of a DMM floats with respect to *ground* and merely provides the means to connect the instrument to an appropriate reference node. Since students learn to use a DMM before they learn to use an oscilloscope, they get accustomed to being able to place its reference lead on any node in the circuit without penalty. Due to the fact that the reference point for many voltage measurements <u>is</u> *ground*, the black lead of the DMM and the *ground* lead of the scope are frequently connected to the same node. The problem arises when the student equates the two reference leads and attempts to measure a floating voltage using a single oscilloscope probe. A basic rule of thumb for oscilloscope usage is to never connect the *ground* lead of its probe to a node that is not already grounded by the circuit. Students frequently forget to follow this rule, and their circuits become unintentionally modified as a result.

A good exercise for reinforcing the distinction between *ground* and *common* involves the construction and measurement of the full-wave rectifier in Figure 8 [Hodges, 3]. This circuit is constructed using a transformer packaged in the ubiquitous plug-in black box usually associated with a DC adapter. The transformer is rated for 1 A_{rms} output at 12 V_{rms}, and it produces an unloaded secondary voltage of about 14.5 V_{rms}. Note that the negative lead of the transformer secondary "floats" with respect to *ground*.

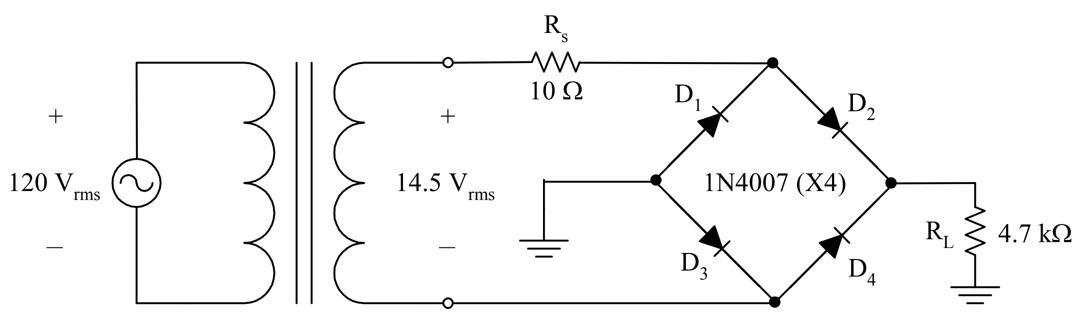

Figure 8: Full-wave Rectifier

When students attempt to construct the circuit in Figure 8, they frequently connect the D_1/D_3 junction and the load resistor "*ground*" to the negative terminal of the transformer secondary. In essence, the students are connecting these nodes to *common* instead of connecting them to *ground*. Thus, D_3 is shorted out, and one side of D_4 loses its path to the transformer. The same effect is produced if the circuit in Figure 8 is constructed properly, but a single oscilloscope probe is used to measure the voltage of the transformer secondary. Figure 9 presents an equivalent circuit for these scenarios. One consequence of this configuration is that the circuit produces a half-wave rectified output instead of the full-wave rectified output that the students expect.

During the positive half-cycle of v_s, the reverse bias across D_1 causes it to block current, while the forward bias across D_2 enables it to conduct current to the load. Since the reverse-biased D_1 can be modeled as an open circuit, R_s can be considered to be in series with R_L. R_s is negligible in this case, so the load current is primarily established by v_s and R_L.

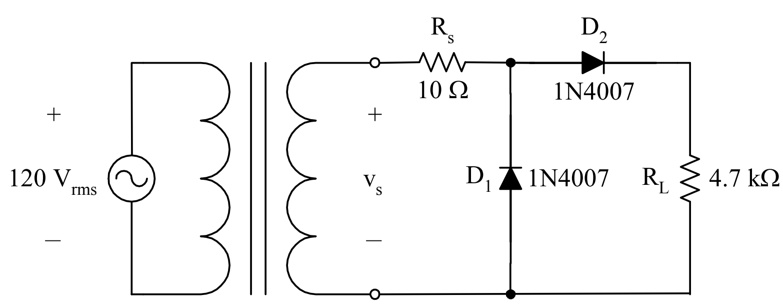

Figure 9: Equivalent Circuit of the "Full-wave" Rectifier When its Common Terminal is Grounded

During the negative half-cycle of v_s, the reverse bias across D_2 causes it to block current from the load, while the forward bias across D_1 enables it to conduct through R_s. The primary purpose of R_s thus becomes apparent: R_s protects D_1 and the transformer during the negative half-cycles of v_s in the event that *common* and *ground* have been erroneously intermingled during circuit construction.

The secondary purpose of R_s is a bit more dramatic. Since nearly all of v_s appears across R_s during the negative half-cycle, and noting that R_s offers a relatively small resistance to v_s, a large current flows through R_s which causes it to start smoking. The pungent odor that subsequently spreads throughout the lab serves as a lingering reminder to all the students that *ground* and *common* are not necessarily interchangeable.

COMMON-BASE AMPLIFIER OSCILLATIONS

A fourth problem that students frequently encounter in the lab relates to poor circuit-construction practices. Students often assume that techniques used to construct low-frequency digital circuits will work in a more general context. An exercise based on the common-base amplifier in Figure 10 [Hodges, 4] can be used as a timely reminder that parasitic effects cannot be ignored in the construction of most circuits. While the circuit in this figure is intended to serve as an audio amplifier, the construction efforts of the typical student are equally likely to produce a 50 MHz oscillator. When the circuit is discovered to be oscillating, attention is forced away from the audio amplifier and toward the efforts required to stifle the oscillation. These efforts usually involve a combination of student activity and instructor assistance.

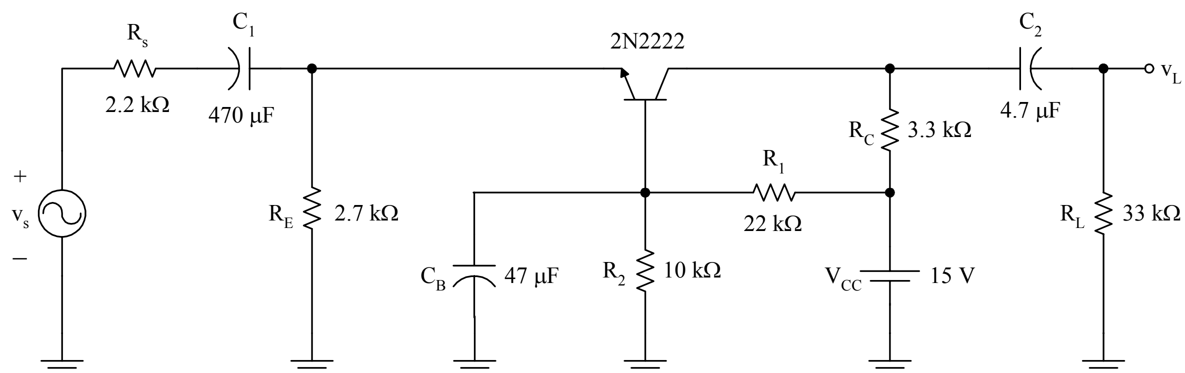

Figure 10: Common-Base Amplifier

Oscillation is possible in this circuit because several factors work together to enable it. The fundamental requirements for oscillation are the existence of adequate forward gain between input and output, and the presence of a suitable feedback path between output and input. Note that a loop is formed by these two paths. A more precise statement of the criteria for sinusoidal oscillation is that the loop gain should be one and the loop phase shift should be zero degrees.

In Figure 10, the transistor provides the gain, while the coupling between the parasitic inductances of component leads and jumper wires provides the feedback. The magnitude and phase of this coupling is affected by the lengths of the leads, the number of jumper wires, the orientation of the leads, and the frequency. From a practical standpoint, the question about whether an amplifier will oscillate depends on whether the transistor produces enough gain at the frequency where the loop phase shift is zero. The unity gain frequency of the 2N2222 is well into the hundreds of MHz, and the common-base configuration produces a considerably wider bandwidth than the common-emitter configuration [Sedra, 5]. Thus, the "amplifier" circuit in Figure 10 is primed and ready to serve in its alternate role of impromptu oscillator.

Undoubtedly, Figure 10 could be modified to make the circuit less prone to oscillation, but a valuable teaching opportunity would be lost in the process. Students are somewhat awed by their first experience with an unintentional oscillator—they are challenged to understand how it oscillates, but they are also intrigued to learn how to transform it back into an amplifier. The experience provided by this exercise provides tangible motivation for using careful layout techniques, shorter lead lengths, and fewer jumper wires. Construction of unintentional oscillators also provides an appropriate context in which to introduce power supply bypassing and twisted-pair connections.

The Role of the Lab Instructor

The role of the lab instructor in implementing this success through "failure" approach is threefold. One important task is to insure that students are well prepared to recognize "bad" data when they see it. This task could include coordinating lab activities with lecture coverage, assigning preliminary work for students to complete before the lab period, or providing a mini-lecture at the start of the lab period.

Another important facet of the lab instructor's role is to be alert to when students need help, and to be adequately prepared to provide that help by being thoroughly familiar with the "learning opportunities" that are embedded in the exercise. At times, this help can be limited to assuring students that they are getting good results while challenging them to resolve the discrepancy between these results and their expectations. At other times, it is more appropriate for the lab instructor to identify the source of the discrepancy. Some students need more help than others, and some are less timid than others about asking for help. The fine line that the lab instructor must walk here is to be approachable as a resource without stifling the ability of the students to function independently. The ultimate objective of this undertaking should be to foster an environment of strategic discovery while preventing students from getting frustrated about getting "bad" results.

An optional, but important task for the lab instructor to perform is to watch for student error patterns and misconceptions that surface in the lab. These observations can then be used to guide the development of lab exercises that target the knowledge and/or skill(s) that the students are lacking.

Conclusions

Experimental "failures" in the laboratory can sometimes provide a more meaningful experience than exercises that proceed like clockwork. Shocking or unexpected results are likely to sustain lasting meaning when they are accompanied by a suitable interpretation. Each of the examples presented previously uses an unexpected event or result to drive home one or more important points.

Exercises can sometimes be crafted to succeed through controlled "failure" and recovery. Exercises can also be written to intentionally target common mistakes and misconceptions through inclusion of a secondary lesson that students can tap into.

References

[1] Boylestad, Robert L., *Introductory Circuit Analysis*, Prentice Hall, Upper Saddle River, NJ, 2003

[2] Boylestad, Robert L. and Nashelsky, Louis, *Electronic Devices and Circuit Theory*, Prentice Hall, Upper Saddle River, NJ, 2002

[3] Hodges, William R., "Laboratory Exercise 12," *ECET 2300 Home Page*, Southern Polytechnic State University, http://ecet.spsu.edu/courseinfo/linear/ecet2300/2300_lab12_rev2_s01.pdf

[4] Hodges, William R., "Laboratory Exercise 9," *ECET 2300 Home Page*, ECET Department, Southern Polytechnic State University, http://ecet.spsu.edu/courseinfo/linear/ecet2300/2300_lab9_rev3_s01.pdf

[5] Sedra, Adel S. and Smith, Kenneth C., *Microelectronic Circuits*, Oxford University Press, New York, NY, 2003

L. Brent Jenkins

L. Brent Jenkins is an Assistant Professor of Electrical and Computer Engineering Technology at Southern Polytechnic State University. He teaches courses in Wireless Communications, Fiber-optic Communications, and Electronics. Professor Jenkins earned a B.S. in Electrical Engineering at the University of Missouri-Rolla, and an M.S. in Electrical Engineering at the Georgia Institute of Technology. He has ten years of teaching experience, four years of industrial experience, and is an active member of IEEE and ASEE.