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Board 94: Work in Progress: Development of Lab-Based Assessment Tools to Gauge Undergraduates' Circuit Debugging Skills and Performance

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WIP: Development of Lab-Based Assessment Tools to Gauge Undergraduates' Circuit Debugging Skills and Performance

Abstract

Debugging is an essential skill in today's integrated circuit (IC) design and new product development. However, this important skill is seldom explicitly taught in college. To design a circuit debugging training intervention, a reliable instrument to assess students' circuit debugging performance and knowledge gain is essential. However, such a domain-specific instrument is not yet available. This paper presents an ongoing effort to design and provide validity evidence for laboratory-based assessment tools to gauge undergraduates' circuit debugging skills and performance. Two example circuits, a non-inverting amplifier and the Greinacher voltage doubler, are used to propose debug assessments covering five common categories of circuit bugs (device orientation, connectivity, equipment settings, misinterpreting datasheets, and issues due to loading).

Introduction

There is a longstanding history of studies in debugging. There are more than 50 years of research related to debugging software with studies ranging from debugging mindsets to identifying common bugs, to improving the debugging skills of novice programmers [1].

Katz and Anderson began their work in improving students' LISP (LISt Processing) program debugging by viewing debugging as a special form of troubleshooting [2]. Chmiel and Loui's work on assembly language debugging focused on training students to perform individual code reviews and group code inspections; while quantitative data were inconclusive, qualitative data showed students found their debugging skills improved through formal training [3]. A recent pre-post-control-group study among German high school students demonstrated the effectiveness of teaching a systematic software debugging strategy at improving students' debugging self-efficacy and debugging performance [4]. In a study looking at the relationship between growth mindset and programming skills in undergraduate students, Scott and Ghinea found that students may have a growth mindset for intelligence in general but hold a fixed mindset for programming aptitude [5]; they conclude that mindset interventions for a student's programming ability should promote discipline-specific changes in mindset rather than general changes. Li et al. conducted a survey of the large body of existing research in software debug education, concluding that teaching debugging knowledge requires training in domain-specific knowledge, understanding both the topography and function of systems to debug, learning globally applicable debug strategies as well as strategies specific to a given program, and gaining experience with debugging [6]. Altogether these works show the need for debug training to help students improve their domain-specific debugging skills and knowledge and develop a growth mindset specific to debugging.

There is a much smaller body of literature in electronics debugging. Fields et al. included both hardware and software debugging in an intervention for a high school course [7]. Students were tasked with creating buggy electronic textile designs for other students to debug resulting in increased "comfort and competence" in future design projects. Nagvajara and Taskin highlight

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the problem of engineering students becoming frustrated or even dropping out due to a perception that hardware debugging skills should already be present, rather than learned in the classroom [8]. A more recent work implemented debugging activities in an embedded systems course and a digital design course to develop students' debugging skills over two semesters of computer engineering content [9]; Duwe et al. noted that their results were limited by using only qualitative data and their "analysis was not designed to identify causal links between course pedagogy and the development of debugging mindsets among students".

These past works clearly indicate the need for debugging education. However, most research has been in software debugging and those works which look at electronics focus primarily on digital design and have not conducted quantitative studies. Our work will move debugging education research forward by conducting a quantitative study on the improvement of students' electronics debugging skills and mindsets through the introduction of domain-specific debug training.

To begin studying improvements in debugging skills, we must first clearly define it. By applying Jonassen and Hung's troubleshooting cognitive model to microelectronics, we define debugging skills as the ability to (1) identify the root cause for any unexpected circuit behavior and (2) take corrective actions to restore the circuit to the desired state [10]. To accomplish these goals, students will need the related skills of general competency in the theory behind circuit design and the topologies and behavior of circuits of interest. Students will also require experience using the oscilloscope, signal generator, power supply, and other equipment available on the lab bench. The required circuit and lab equipment knowledge is already incorporated into Fundamentals of Microelectronics, the course where this debug training will be implemented.

To collect the desired quantitative data a reliable instrument to assess students' circuit debugging performance and knowledge gain is needed. The remainder of this paper outlines our current efforts to design and provide validity evidence for laboratory-based assessment tools to gauge undergraduates' circuit debugging skills and performance. To begin we must first determine the range of circuit bug categories the assessments must cover. After this we look at two circuits used in Fundamentals of Microelectronics labs that can be adapted to create debug assessments. One example buggy circuit assessment is explained in full detail along with four additional examples to cover the full range of topics. Finally, the recommended usage of the instrument and validation plan are discussed.

Intended Coverage of Instruments

As a starting point for selecting buggy circuits for students to debug, we have identified five common classes of errors. These errors are based off bugs students have encountered with their circuits in Fundamentals of Microelectronics labs and corroborated by industry debugging resources [11]-[13]. The order of the list only reflects the order the bugs will be discussed in this paper and not necessarily their frequency or severity.

1. Incorrect device orientation
2. Connectivity issues
3. Improperly setting equipment
4. Misinterpreting datasheet specifications
5. Unexpected behavior due to circuit loading

First is device orientation. It is easy to rotate an IC leaving the pins in an unexpected location before soldering or placing the IC in a breadboard. With pins in an unexpected configuration, the necessary power, ground, input, and output connections will not be wired correctly. The IC may seem completely dead after power is supplied or there may be unpredictable output behavior.

Connectivity issues come in two varieties. If a component is not properly soldered/placed on the breadboard, it may not actually connect to the rest of the circuit, leading to an open circuit. In other cases, two or more components that are supposed to be separated may be unintentionally connected. The resulting short circuit could simply lead to incorrect outputs or permanently damaged components.

Part of the domain knowledge required to debug circuits includes properly handling the lab equipment required to operate and measure a circuit. The large variety of settings present on multimeters, power supplies, signal generators, and oscilloscopes as well as the different uses for specialized probes and connectors leads to many avenues for improper circuit behaviors due to equipment use errors.

When a datasheet is misinterpreted, it can have many different effects on a circuit. A student may misunderstand the purpose of a pin on an IC, select a component incapable of handling the power in the circuit, or run into many other issues. Because of this misunderstanding, a circuit could display issues from minor performance discrepancies to complete circuit failure.

Behavior issues due to loading may involve anything from rapid discharge of capacitors due to a low resistance load to sluggish response caused by a high capacitance output node. A circuit may be fully functional while still exhibiting errors at the output because of these loading bugs.

Although there are other error sources such as those caused by extra impedance introduced by traces between components on a printed circuit board (PCB), these advanced topics fall outside the scope of current plans for the debugging training in Fundamentals of Microelectronics.

Circuits for the Instruments

With the coverage goal in mind, we have selected two target circuits students learn to use during existing lab modules as starting points for creating debug assessments. First is a simple non-inverting amplifier (see Fig. 1) students use early in the semester implemented with a TL074 op amp [14]. The output voltage (V_O) will be the input voltage (V_I) multiplied by a gain of $1 + R_F/R_I$ [15]. Students also learn about the frequency dependence of the op amp and use an oscilloscope to make a basic Bode plot of the change in gain with increasing frequency. Finally, students are taught why the op amp must have biasing at ± 15 V for proper operation.

Second is the Greinacher voltage doubler [16] (see Fig. 1) where V_I is a sinusoid and V_O is a DC signal (with slight ripple) approximately equal to double the peak voltage of V_I. In the lab documents, students are told $D_{1,2}$ should be Schottky diodes to ensure a low voltage drop across each diode. This helps the circuit achieve an output as close to the ideal value as possible. During the lab students must experiment with different values of source resistor (R_S) and load resistor (R_L) to see how too high of an R_S and too low of an R_L can adversely affect the output.

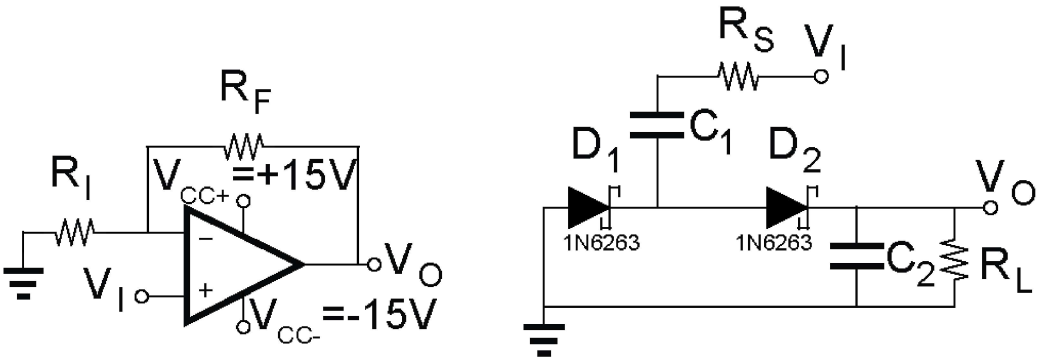


Fig. 1: A non-inverting amplifier (left) and The Greinacher voltage doubler (right).

While completing these labs (and other lab units in the course) students also gain familiarity with properly operating lab equipment to help design and test their circuits. Of note, students are taught about the two modes of the lab's oscilloscope probes: a higher capacitance mode that measures the voltage of the connected node with no attenuation, and a mode that reduces both capacitance and voltage by a factor of ten. In addition to this, students are expected to record key information from datasheets for important components in each lab's circuits (such as op amp parameters, diode voltage drop, etc.) to gain practice with datasheet literacy. The added domain knowledge of proper equipment usage and datasheet literacy broadens the range of bugs students should be prepared to handle.

Example Instrument: Incorrect Device Orientation

In the first buggy circuit, a PCB with all the proper components for a non-inverting amplifier using a TL074 op amp will be connected to the power supply (± 15 V), signal generator (1 kHz sinusoidal input with peaks at ±1 V), and oscilloscope (channel 1 on input and channel 2 on output) with all component connections installed correctly (no shorts or open circuits and PCB layout matching circuit schematic); however, the TL074 will be rotated 180°. As shown in Fig. 2, this rotation swaps pins 1-7 with pins 8-14. With the rotated IC, all input and output connections are correct (simply using op amp 3 instead of op amp 1), but the +15 V and -15 V connections are swapped. Students will be given a buggy PCB, the lab handout shown in Table 1, and the TL074 datasheet [14].

The correct PCB installation and the associated schematic are shown in Fig. 3. The groove at the top of the IC indicates pin 1 is at the top left of the PCB, leading to the expected locations for V_{CC+} and V_{CC-}. Fig. 4 shows the oscilloscope output. In channel one of the oscilloscope (top half of the screen) a 1 kHz sine wave with peaks at ±1 V is visible, while channel two (bottom half of the screen) shows a 1 kHz sine wave with peaks at ±10 V. Fig. 5 shows the buggy PCB installation given to students during the assessment and the related buggy schematic. The groove is now at the bottom of the IC, giving a visual indication of the bug which flips the V_{CC+} and V_{CC-} connections as shown in the schematic. The resulting oscilloscope measurements the student will see when they begin the debug exercise are shown in Fig. 6. In channel one of the oscilloscope (top half of the screen) a 1 kHz sine wave with peaks at ±1 V is still visible, but now channel two (bottom half of the screen) shows the output is stuck at ground.

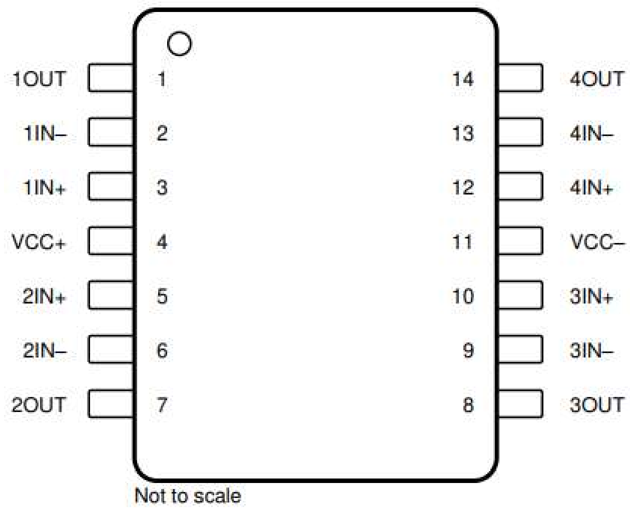
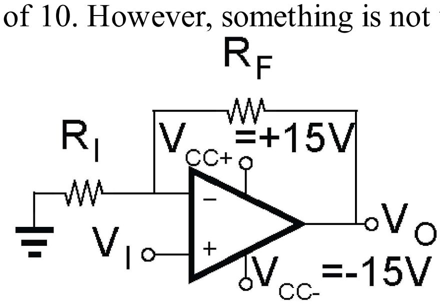


Fig. 2: Pinout of the TL074 family of ICs [14]

Debug Exercise 1:
The provided PCB is meant to implement an op amp-based non-inverting amplifier with a gain of 10. However, something is not working correctly.



Gain = (R_F / R_I) + 1
R_F = 9kΩ
R_I = 1kΩ
V_I is a 1 kHz sine wave with peaks at ±1 V
The op amp is on a TL074 IC

Please answer the following:

1a. What was the cause of the problem? Answer: ____________________
1b. How did you find the problem? Answer: ________________
2. How to fix the problem? Answer: ________________
3. Can you demonstrate a fix to the circuit? (Please request access to tools and instrument in the laboratory as needed.) [Demonstration needed.]

Time limit: 15 minutes.

Table 1: Lab handout for incorrect IC orientation debug assessment instrument

In using this instrument, we will collect the following information: the student's written answer to and time required to answer parts 1 and 2, the student's hardware demonstration and time to complete part 3, and the debugged circuit's gain compared to the ideal gain (if part 3 was completed).

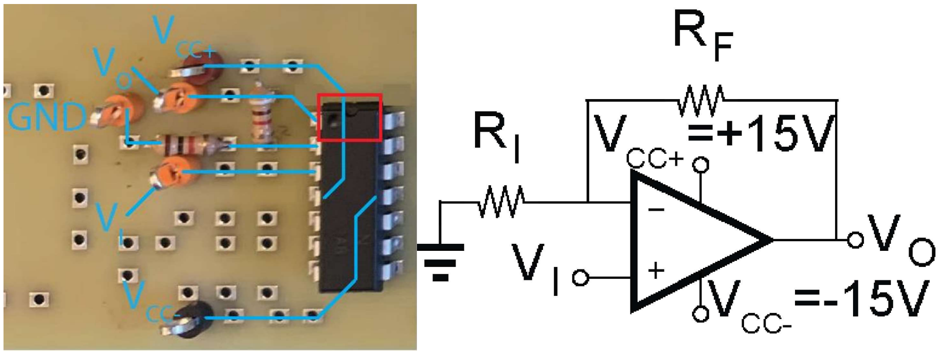


Fig. 3: Correct PCB (left) and the associated schematic of a non-inverting amplifier (right)

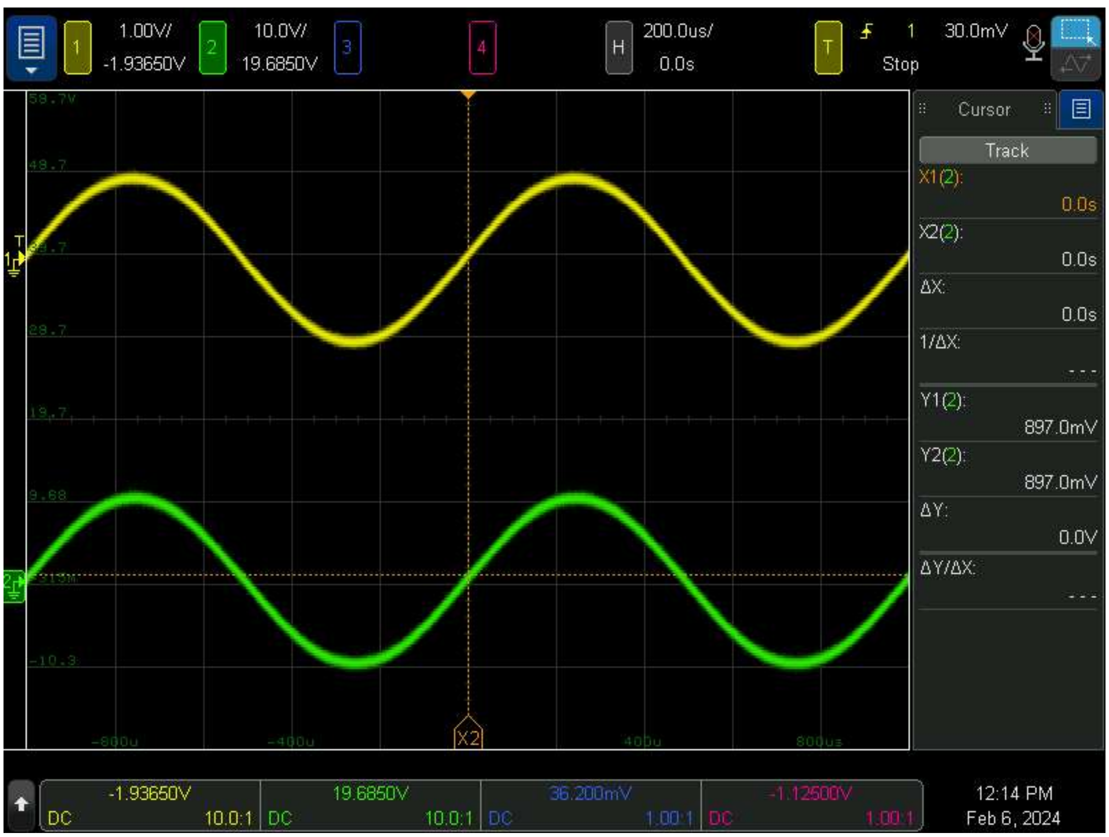


Fig. 4: Input (top trace) and output (bottom trace) to correct PCB achieving gain of 10

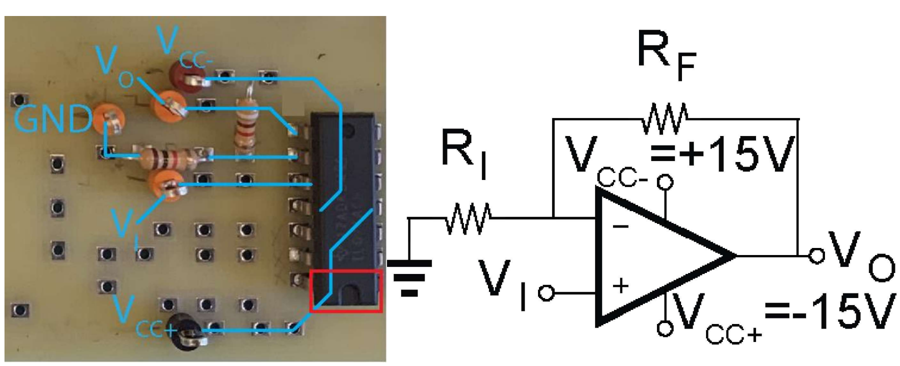


Fig. 5: Buggy PCB (left) and the associated schematic of a non-inverting amplifier (right)

To successfully debug the circuit, students will need to examine the datasheet to find the pinout diagram of the TL074. Comparing the pinout to the provided circuit diagram should quickly reveal that the circuit is not receiving the correct power. There are two ways to fix this device orientation bug. First, a student may decide to use a reflow gun to remove the IC from the PCB and then resolder the IC in the expected orientation. This method will be challenging to complete within the allotted time for the assessment, but there is a much simpler solution that requires more datasheet literacy. A student can swap the wires connected to V_{CC+} and V_{CC-} to achieve the expected circuit performance using op amp 3 instead of the expected op amp 1.

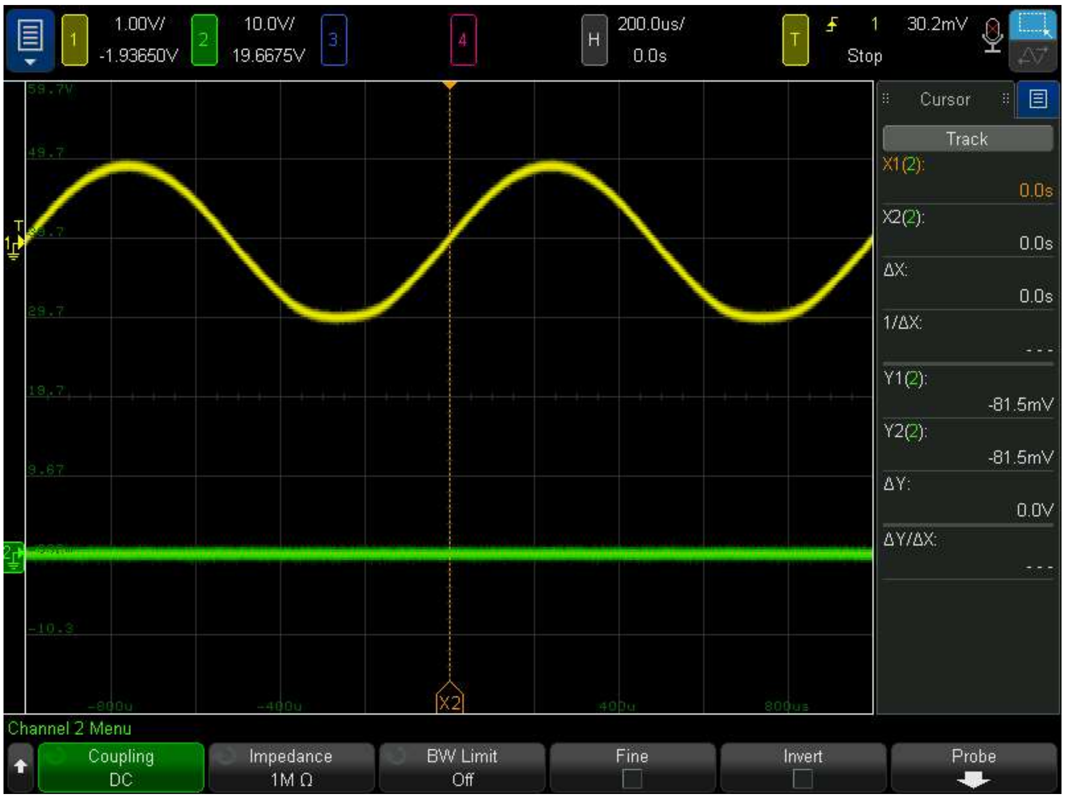


Fig. 6: Input (top trace) and output (bottom trace) of buggy PCB achieving no gain

This debug exercise was created to assess a student's ability to identify circuit problems caused by incorrect device orientation. Successfully identifying the solution primarily requires datasheet literacy to identify the cause and possible solutions. To a lesser extent, the assessment will require familiarity with lab equipment to understand buggy outputs, verify the bug is not caused by lab equipment, and to evaluate performance after attempting a fix for the circuit. In addition, general familiarity with op amps and circuit design will be required to complete the assessment in the given time. We expect a novice student with little to no debugging experience will not be able to answer parts 1 and 2 within the allotted time. We expect a student with some debugging skills to answer parts 1 and 2, but they may not identify the fast solution of swapping connections and are not likely to have time to desolder and resolder the IC within the allotted time. We expect a student with strong debugging skills to complete the live demonstration of part 3 within the allotted time.

Additional Circuit Examples

For brevity, only the full details of the incorrect device orientation evaluation are presented in this paper. The summaries of other buggy circuits discussed below will use evaluations with the format presented above.

Connectivity Issues

Once again using the non-inverting amplifier, students will have to identify one of two different bugs caused by connectivity. The input is sinusoidal and all connections to lab equipment should be set according to the expected values provided to the student in the schematic. All parts should match those provided to the student. As shown on the left of Fig. 7, a short circuit is present where R_F should be (this could, for example, be caused by solder connecting the two terminals of a resistor). The result is an output with no gain (because R_F is now 0 Ω the gain becomes $0/R_S$ + 1 simplified to 1).

As with the prior assessment, students will be given the buggy non-inverting amplifier circuit and the TL074 datasheet. Students will have multiple potential bugs to rule out. First, due to their training on the frequency dependent characteristics of the op amp, it is reasonable to verify the input is at the correct frequency and not some higher value that would attenuate the signal. Students might also check that RF and RI are the correct values, as values not matching those of the schematic could make the gain approximately 1. This investigation into the resistor values may lead students to discover the short circuit at R_F, if not students should eventually check the continuity of components which will quickly reveal the issue.

In the second version of the circuit (see the schematic on the right side of Fig. 4) instead of a short circuit, there is no connection at one of the terminals of R_F resulting in an open circuit (potentially an unsoldered connection or a resistor not fully installed in a breadboard). In this case the output signal (V_O) will saturate at +15V and –15V like a square wave as the input signal oscillates between its maximum and minimum values.

The list of potential causes a student might investigate on their way to the root cause of the bug is similar to the potential causes of the short circuit. Students may suspect incorrect resistor values or an improperly set input signal amplitude. Students should eventually check continuity while verifying the circuit matches the schematic to discover the cause of the bug and fix it.

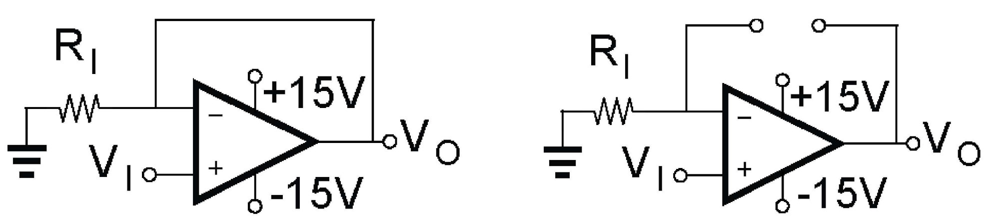


Fig. 7: Non-inverting amplifier with a short at R_F (left) and open circuit at R_F (right)

Improperly Setting Equipment

Bugs in the non-inverting amplifier do not need to be the fault of any component in the circuit. Incorrect settings on lab equipment can also lead to unexpected behavior. Once again, students will have a PCB or breadboard with a non-inverting amplifier on it along with a schematic of the expected circuit noting expected performance and proper settings for lab equipment. Signal generator and power supply connections will be done properly. While oscilloscope probe locations will be correct, the probe connected to V_O will be set to the 10x capacitance reduction mode. This will introduce a 10x reduction in the gain as measured by the oscilloscope.

Students will again have many places to check for bugs. With a reduction in gain, students are likely to check the frequency and amplitude of the input to verify it is correct. They may also check resistor values and the connectivity of all devices in the circuit to ensure all circuit elements are performing properly. This debugging assessment may challenge students since it depends heavily on domain knowledge that is often taken for granted. There is seldom a reason for the students to consider the oscilloscope probe as anything more than an ideal wire, but prior training in the lab has given them the domain knowledge necessary to identify the root cause *if they include signal probes in their problem space*. The unique challenge of this assessment makes it a valuable addition to check students' full range of debugging capabilities.

Misinterpreting Datasheet Specifications

The variety of diodes available for students' circuits leads to another avenue for testing debugging skills, verifying a circuit is using the best component to complete a circuit's purpose. In this assessment, students will be given datasheets for the various diodes available in the lab as well as a Greinacher Voltage Doubler using the components in Fig. 8 with properly set up connections to a signal generator and oscilloscope, but the intended schematic provided to the students will match the voltage doubler shown in Fig. 1. The assessment handout will also list a range of acceptable values for R_S and R_L (this will ensure no difference in materials provided for other debug assessments involving the voltage doubler). The intended V_O will be listed with the schematic and results from oscilloscope measurements will show the maximum V_O value does not reach the desired voltage from the schematic. This is due to using diodes with a higher voltage drop than that of the intended Schottky diodes.

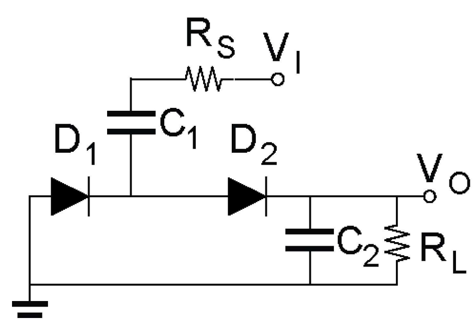


Fig. 8: Greinacher Voltage Doubler using diodes with larger voltage drop.

This circuit poses a unique challenge for students. This circuit's performance is close enough to the expected behavior that identifying the symptom may take longer. After identifying the problem, it may take time to consider checking the part number shown on diodes used in the circuit compared with the part number of the schematic. Even knowing the diodes do not match the ones intended in the schematic, students may not realize this discrepancy is the problem and if they do it may take time to identify why it is the problem. This assessment will challenge students to incorporate domain knowledge of datasheet literacy into their debugging skills.

Unexpected Behavior Due to Circuit Loading

Debugging of loading effects can also be assessed with the Greinacher Voltage Doubler. Students will be given the voltage doubler as depicted in Fig. 1 along with the appropriate diode datasheets and schematic detailing output characteristics. The assessment handout will also list a range of acceptable values for R_S and R_L. In this case the load resistor R_L is set to a value that is too small and allows capacitor C_2 to discharge too quickly leading to an output voltage ripple outside specifications.

Because students were required to experiment with various source and load resistors in the original lab assignment and noted the performance issues caused by small R_L and large R_S, they have practice with the domain knowledge to properly assess the situation and diagnose the problem. During their search for the root of the problem, students may check for errors with input frequency or examine continuity of devices to rule out a short circuit at the output node. Their existing experience with the circuit should lead them to examine permissible load resistor values and diagnose the problem.

Recommended Usage of the Instrument

To measure student debugging skills, unannounced debugging tests will be incorporated into the lab schedule throughout the semester. To measure improvement in debugging skills we propose to collect the following quantifiable information: (1) Time to debug the faulty circuit (split into time to identify the bug and time to fix the bug) and (2) performance parameters of the debugged circuit, such as gain, power consumption, and voltage ripple.

To measure only debugging skills it is important to isolate these skills from related technical knowledge the course also introduces. For example, if students are debugging the non-inverting amplifier circuit, we will provide a schematic of the circuit and a description of its intended operation. It goes beyond the content domain of a test focused on debugging skills to require memorizing the topology or intended operation of the circuit; struggles with other course content should be isolated from debugging content, when possible, to avoid construct-irrelevant variance (test scores being impacted by factors outside the test's intended purpose [17]).

Time to identify faults in the circuit and suitable fixes helps measure students' abilities at various stages of debugging as outlined by [10]. First, a timely debug process is dependent on accurately constructing a list of errors the circuit may have (the problem space). To accomplish this, students must have a working knowledge of the theory behind circuit design (Ohm's Law, Kirchhoff's Voltage and Current Laws, etc.) and some general familiarity with the circuit under test. A well-constructed problem space will allow students to test for faults associated with the potential problems in the circuit, rather than running tests by a trial-and-error approach. Identifying faults leads to determining the problem or problems in the circuit in a timely manner. Finally, students will have to identify and implement a solution to the problem(s).

Part of learning debugging skills is verifying the implemented solution has achieved the desired result. For this reason, we will also collect data on the circuit's performance after debugging. Since students are provided with a list of parameters the circuit is expected to achieve under typical operating conditions, the result of debugging should return the circuit to operating completely within the conditions specified. By providing the expected performance parameters rather than expecting students to memorize them, debugging evaluations will once again avoid construct-irrelevant variance.

Validation Plan

Since we are designing a new, custom, domain-specific evaluation instrument, we will take extra steps to ensure the reliability and validity of the content. We will follow the American Psychological Association (APA)'s standard on Educational and Psychological Testing [17]. However, the validation efforts should be carefully guided by further ethical and equitability considerations like those outlined by Sochacka, Walther, and Pawley [18] to ensure our debug assessments do not unfairly advantage some engineering student populations over others. These debug education efforts will be monitored by **an industry advisory board** that will meet at least once every semester. Representatives on the board have expertise in a wide range of electrical engineering disciplines (e.g., RF, internet-of-things, power management) and come from different sized companies across the country. The breadth of electrical engineering disciplines and experiences at different sized companies in geographically distinct locations will help ensure results from the debugging curriculum development hold relevance across the electrical engineering industry. Results from the spring semester will be presented to the advisory board during the summer leading to changes made to the debugging curriculum for the fall semester. A meeting in December or January will inform changes for the spring semester. This cycle will continue throughout the curriculum development process.

Validity testing can take many forms; while our industry advisory board is a key part of validation, other developments in engineering education help guide our efforts to thoroughly validate our new assessments. For example, DeMonbrun et al. included classroom observations and cognitive interviewing alongside advisory board reviews to refine their instrument for student responses to instructional practices in engineering courses [19]. Existing validated studies in engineering education such as the undergraduate students' engineering self-efficacy study from Mamaril et al. [20] and the design thinking study for first year and senior engineering from Coleman et al. [21] also help inform the statistical analysis we will need to properly validate our debug assessments.

Conclusion

This paper highlights the initial efforts towards developing lab-based assessments of students' debugging skills. We have defined debugging skills students are expected to develop, proposed one debug assessment and additional circuits for assessments that will cover a range of common bugs, and outlined the recommended way to use the instrument. Throughout the design process we are consulting the American Psychological Association's standards on Educational and Psychological Testing and regularly meeting with our industry advisory board to improve the validity and reliability of evaluations.

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