Engineering Educators Bringing the World Together
2025 ASEE Annual Conference & Exposition
Palais des congrès de Montréal, Montréal, QC • June 22–25, 2025
Paper ID #47288

BYOE: Teaching and Assessing Troubleshooting Strategies in Circuits Courses

Dr. Caroline Crockett, University of Virginia

Caroline Crockett is an assistant professor at the University of Virginia in the Electrical and Computer Engineering department. She received her PhD degree from the University of Michigan in electrical engineering. Her research interests include image processing, conceptual understanding, and troubleshooting.

Mr. Adam Barnes, University of Virginia

Adam Barnes graduated with a BS and MS in Electrical Engineering from Virginia Tech. He worked in small business and industry for 18 years before returning to Virginia Tech to teach engineering as a professor of practice. He then moved to Charlottesville and began teaching at the University of Virginia in the Electrical and Computer Engineering Department, where he has now been for 5 years.

Dr. George Prpich, University of Virginia

Professional Skills and Safety are my main pedagogical interests. I use the Chemical Engineering laboratory to implement safety training to improve safety culture, and to adapt assessment methods to enhance development of students' professional skills. I am an Assistant Professor of Chemical Engineering at the University of Virginia and I hold a B.Sc. (University of Saskatchewan) and Ph.D. in Chemical Engineering (Queen's University). Complimenting my pedagogical research is an interest in bioprocess engineering, environmental engineering, environmental risk management, and I have authored >40 peer reviewed publications in these fields. I'm also active in developing workforce development initiatives, specifically within the biopharmaceutical manufacturing space. Beyond academia, I have 7+ years of international consulting experience working with the U.K. government, European Union, and the United Nations.

Dr. Anne Marguerite McAlister, University of Virginia

Dr. Anne M. McAlister is an Assistant Professor in the First Year Engineering Center at the University of Virginia. She has her PhD in Education and MS in Systems Engineering from the University of Virginia, and her BS in Chemical Engineering from The Ohio State University. Her research focuses primarily on identity and qualitative research methods.

BYOE: Teaching and Assessing Troubleshooting Strategies in Circuits Courses

Abstract

This bring your own experiment (BYOE) paper details two breadboard-based laboratory frameworks designed to teach and assess electrical and computer engineering students' use of troubleshooting strategies. Both frameworks require only the use of basic circuit hardware, including a breadboard, a power supply, an oscilloscope, and components such as op-amps and resistors. This paper discusses the set-up of both troubleshooting frameworks, including example circuits, practical notes on running the exercises in classes ranging from 40 to 100 students, and suggestions for how to collect and analyze the resulting data for instructional or research purposes.

1 Introduction

One goal of laboratory instruction is that students learn how to troubleshoot a system. Troubleshooting refers to a process, typically methodological, to identify and repair faults in a system. In their paper "The Role of the Laboratory in Undergraduate Engineering Education," Feisel and Rosa [1] mention troubleshooting in both their "design" and "learn from failure" learning objectives.

While expert troubleshooting requires domain knowledge of the specific faulty system, many troubleshooting strategies are "global strategies" in the sense that they apply across domains [2]. Despite their broad relevance, troubleshooting strategies are rarely explicitly taught or assessed in engineering laboratories. This is in stark contrast to computer science, where debugging skills are a common learning objective and there are many research studies assessing the effectiveness of ways to teach debugging [3]. Explicitly introducing troubleshooting strategies within an engineering curriculum, similar to the way debugging is taught, may ensure more consistent instruction than relying on "inevitable" errors as teaching tools during lab [4]. Explicit lessons on troubleshooting may also help students develop metacognitive strategies that aid in transferring troubleshooting knowledge between disciplines [5].

This paper presents two frameworks for bringing troubleshooting instruction and assessment into an electrical and computer engineering classroom via breadboard experiments. We use the Analog discovery 2 as the power source, signal generator, and oscilloscope [6], with a custom breakout board to connect it to a standard breadboard, but the troubleshooting frameworks generalize to any standard breadboard set-up with an oscilloscope or multi-meter.

2 Background: Troubleshooting strategies

The learning objectives of both troubleshooting frameworks are to: be able to name and give examples of multiple troubleshooting strategies, be able to identify troubleshooting strategies in example problems, and gain meta-cognitive awareness of your own troubleshooting process. Here, we list some example global troubleshooting strategies and explain them in the circuits context: [2], [7]:

1. **Trial and error:** trying different solutions until the problem is resolved.
2. **Exhaustive strategies**: involves thorough examination and testing of all possible causes to pinpoint the issue. There are two main forms that this strategy takes:
   - **Considering alternatives**: Considering possible reasons why a specific issue is occurring and
   - **Rebuilding**: Taking apart the whole circuit or a section of the circuit in an attempt to rebuild it correctly.
3. **Topographic**: focuses on understanding the system's structure and components to trace the source of the problem. In circuits this often takes the form of **tracing**: Reviewing the flow of voltage and current in the circuit, referencing the schematic, typically starting from the input.

4. **Split-half**: divide the system into parts and isolate the problem by testing each section separately.
5. **Discrepancy detection**: emphasizes the identification of discrepancies or deviations from expected system behavior to locate faults. Three common forms this strategy takes are:
   - **Output testing**: Using an oscilloscope to view an output signal;
   - **Gain domain knowledge**: Reviewing specifications, reexamining the desired output, or reviewing analytical derivations to gain insight; and
   - **Pattern matching**: Fixing something that does not look "right", such as adjusting a component because the reference designator is misoriented, or cross referencing between experimental and expected outputs.

Some strategies, such as split-half and discrepancy detection, are methodical and scale well to complex systems. Other strategies, such as trial and error and rebuilding, often work well for small systems, but do not scale well.

3 Troubleshooting framework: Telephone troubleshooting

The first framework, which we call 'telephone troubleshooting,' requires students to work in teams of two to three. Each team assembles a circuit they designed from a previous lab. Fig. 1 shows the circuit used for this troubleshooting exercise, which uses a photoresistor and a comparator to turn an LED on and off depending on the light level in the room. We chose this circuit specifically because the students are familiar with how it functions, having designed the values for all resistors the previous week. We believed that specific domain knowledge and prior experience with the circuit would help students to hypothesize what may be wrong with the circuit given specific erroneous behavior, and thus students may use more sophisticated troubleshooting strategies such as split-half, rather than relying on tracing.

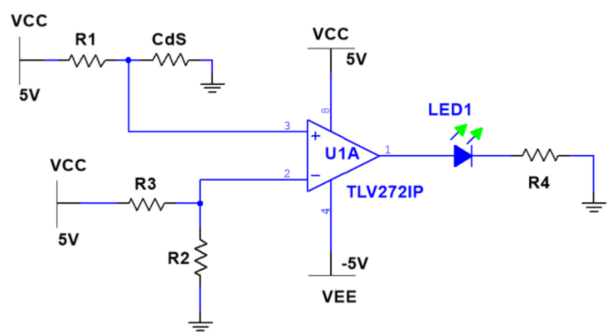


Figure 1: Light switch circuit schematic. The circuit uses a CdS photoresistor to detect light levels and an op-amp configured as a comparator to turn the LED on or off.

3.1 Telephone procedure

Once the every group member has a version of the circuit built and verified for proper operation, the instructor or teaching assistant (TA) purposefully broke the circuit in one of three prescribed ways. In previous semesters, the student teams would break the circuit and exchange it with another team. This was done to allow the exercise to scale to large classes. However, this process did not work well because the students did not break the circuits in a uniform fashion. Further, because they worked at different rates, some teams were left waiting for the group they exchanged with to finish before being able to proceed. Having the instructor or TA break the circuit provides a more uniform experience, although it does require more TAs to scale it up for larger classes.

Each student on the team takes one of three roles. The chief engineer directs the troubleshooting, the technician takes measurements, and the record keeper documents the tests performed and their results. For teams of only two students, the chief engineer also acts as the record keeper.

- **Chief engineer**: The chief engineer is tasked with determining what is wrong with the circuit. However, they are not allowed to directly examine the circuit – they must get all their information from the technician. They essentially have to troubleshoot the circuit as if they were helping a customer over the telephone, where they cannot physically observe the circuit themselves, only the circuit schematic. The purpose of this is to force the student in the role of chief engineer to analyze the circuit behavior to determine what might be wrong rather than just staring at the circuit and hoping to spot the error or overly relying on the tracing strategy [7]. The chief engineer tells the technician what scope measurements to take and what connections to change to determine what is wrong with the circuit.

- **Technician**: The technician must clearly describe how the circuit is behaving. Even if it is obvious to the technician what is wrong with the circuit, they should only give information to the chief engineer that they are asked for. The technician takes measurements and reports results to the chief as directed and follow directions on what connections to change.
- **Record keeper**: The record keeper documents the technician's observations of the circuit, the measurements that the chief engineer directs and the reasoning behind making those measurements. The record keeper should facilitate communication, making sure that the chief's directions are precise and the technician's responses are clear. This allows the troubleshooting process to be documented so the team can reflect on the process afterward.

Once the chief engineer figures out what is wrong with the circuit, they direct the technician to fix it. Then the team members swap roles and the instructor or TA breaks the circuit again in a different way for another round of troubleshooting. Each team member should have a chance to play every role.

While we have only tested this telephone troubleshooting in a circuits course, the general process could generalize to many engineering laboratories.

3.2 Instructor Reflection and Notes

Each troubleshooting session was graded independently and the students did a good job fixing the problems introduced into the circuit. Most students followed the directions. However, despite the lab instructions and a discussion of how the troubleshooting was supposed to be performed at the beginning of class, some chief engineers still looked directly at the circuit or asked the technician to do the looking for them rather than taking measurements to determine what was wrong with the circuit. In a small class, this can be easily monitored, but in a large class, it is difficult to monitor how well everyone is performing the lab. Although it would be an additional logistical burden, the exercise might be improved by using a screen to keep the chief engineer from being able to see the circuit, or by having the students sit separately and communicate with each other via their phones, literally making them troubleshoot over the phone.

4 Troubleshooting framework: Observing troubleshooting

The second troubleshooting framework similarly involves having students repair circuits with known faults. However, the troubleshooter is now able to see and directly interact with the circuit. This framework places more emphasis on meta-cognition by having students observe another student troubleshoot and record which troubleshooting strategies they used. We considered pairs of students, but the method would easily generalize to larger groups.

4.1 Pre-class content

Before class, students watch a sequence of three videos, totaling just under half an hour. The introductory text to the first video is the list of troubleshooting strategies from Section 2. The first video (13.5 minutes) overviews these strategies and provides examples of what those strategies look like using the circuit in Fig. 2. The fault was an extra wire connecting the inverting terminal of the op-amp to V_{out}, causing the op-amp to act as a voltage follower. As a few examples of going through the troubleshooting strategies, we demonstrated:

1. the trial and error strategy by moving R_1 from the V_{CC} connection to the op-amp output pin and randomly moving the op-amp power wires
2. the considering alternatives strategy by listing errors such as flipping resistors, the power supply being off, and the op-amp railing due to a missing negative feedback connection; and
3. the split-half strategy by testing the voltage at the non-inverting terminal to determine if the error was in the voltage divider or op-amp.

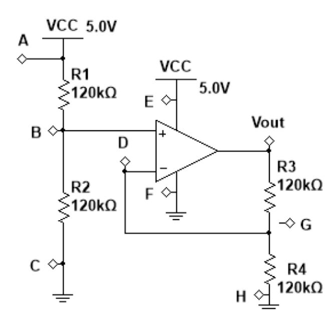


Figure 2: Example circuit for the introductory pre-class video.

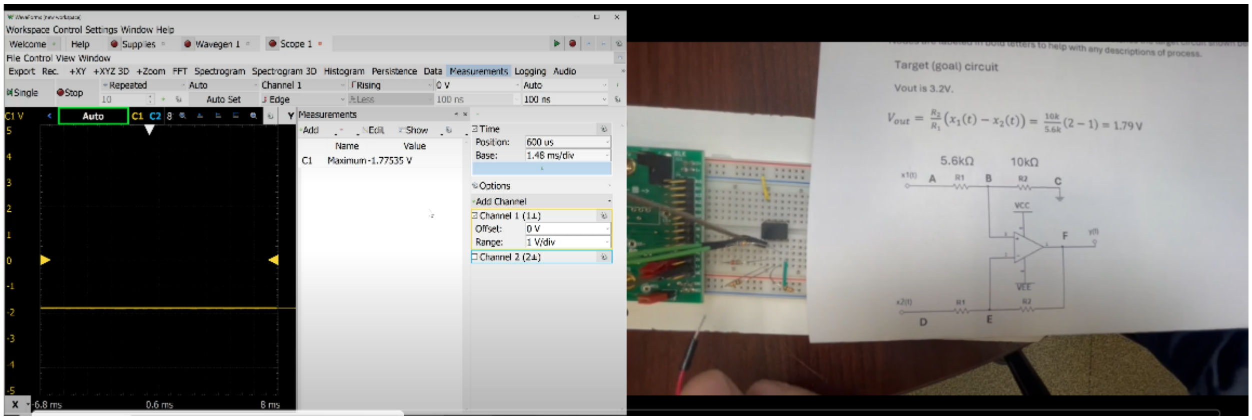


Figure 3: Screenshot from the pre-class example troubleshooting video. The left pane shows the oscilloscope window on the computer. The right pane shows the breadboard and the reference schematic.

The second video (6.5 minutes) has the following introduction: "The next video walks through the observation protocol that we will be using in class. The goal of doing observations is to practice recognizing strategies. This practice should help you develop metacognitive awareness of the troubleshooting process. This is incredibly valuable as much of your time in this class will be spent finding errors in your code or physical devices!" Appendix A shows the first page of the observation protocol, which consists of a table where students mark which troubleshooting strategy they observe. The purpose of the second video is to familiarize students with the layout of this table. The back side of the page continues the table to capture additional troubleshooting steps, then has reflection questions for the observer.

The introduction for the third video (3 minutes) is "The final pre-class video has an example of Prof. Crockett troubleshooting a circuit. The goal is to help you practice identifying troubleshooting strategies and get used to the worksheet so that you are prepared for our in-class exercise. As you watch the video, fill out the observation worksheet [link to file]. Please watch the video at normal speed and do not rewind; you will not be able to do that in class." We used a split screen to show both the camera video capture of the circuit and the computer screen where we had the datasheets and troubleshooting task overview open. Fig. 3 provides an example screenshot from this video. Here, the circuit is a differential amplifier and the fault is that the input voltages are reversed, resulting in a minus sign error in the final value. The instructor purposefully used many different troubleshooting strategies and did not jump directly to the correct answer. Instructors can use the students' submission of the observation worksheet from this practice observation to verify that students understand both the definitions of the troubleshooting strategies and how to use the worksheet. Researchers can use these data as a rough measure of inter-rater reliability since the data reveal how consistently students label troubleshooting steps.

We recorded all three videos using Panopto. We provide the video times as a rough guide, but we expect that having each instructor create their own videos is a key step to achieving student buy-in to the importance of this troubleshooting activity. A reasonable modification would be to replace the first two videos with the provided text description and an instruction to read over the observation worksheet. We tested this troubleshooting framework in a flipped style course, so video recordings were a familiar medium to our students.

4.2 In-class troubleshooting observations

The in-class troubleshooting activity begins the same way as for telephone troubleshooting: students build and verify a circuit according to a given design. However, in this activity, every member of the group builds a circuit they have not seen before. Students then break the circuit in a specific way, such that all students who troubleshoot that circuit will be searching for the same set of faults. Appendix B presents two examples of task sheets to hand out in class. Logistically, every student needs access to the observation worksheet (hardcopy or online); datasheets for any components in the circuit; and instructions on how to build, verify, and break one circuit.

Students then take turns troubleshooting a circuit while their group members fill in the observation protocol. After each troubleshooting round, both the troubleshooter and observer answer reflection questions. We found 5-10 minutes to be sufficient for troubleshooting time depending on the level of the class and how familiar students are with the circuit components.

4.3 Instructor Reflection and Notes

Overall, the students picked up the observation worksheet very quickly and wrote a surprising amount of notes, making this a promising approach for gathering data for assessment and research purposes.

While developing and piloting these troubleshooting exercises, we ran into a few logistical challenges. First, we initially tested the observational approach with TAs building the faulty circuits. This leads to more uniformity in the circuits, but is impractical for large courses. Second, we found that some students will write a surprising amount for the reflections; giving them enough time to finish those after each troubleshooting round can be untenable. Instead, we gave students only a minute to write down quick thoughts, then provided more time after all troubleshooting rounds for students to finish all reflections. Finally, it is important when designing the faulty circuits that all equipment is easily accessible to students. We purposefully designed many of the faulty circuits to not require a waveform input so that, when TAs were building all the circuits, we could build many circuits on the same breadboard without worrying about moving the input location between rounds.

At the end of the semester, we asked students how they would feel if the assignment were graded based on correctness rather than completion. The majority of the class (32 out of 35) selected either that they would have no concerns, they would have no concerns if there was an additional ungraded practice and/or partial credit, or that they they 'would have been a bit nervous, but would think it is a fair assessment." The remaining three students thought they would have been too nervous to perform their best if the exercise were graded. The time limit was necessary for our class logistics, but, if assigning the troubleshooting exercise for a completion grade, we recommend increasing the time limit and offering students the chance to try multiple circuits and only keep their highest grade.

5 Conclusions and future work

This paper presents two frameworks for practicing troubleshooting skills in the classroom. We have developed and piloted these in circuits courses, but expect that they can generalize to laboratory courses in other disciplines. The uniformity in faults in both frameworks allows for comparison of student approaches and success, making these frameworks promising for student assessment and research purposes. Work is ongoing to study how effective these frameworks are at teaching and assessing troubleshooting. For future work, we plan to report results measuring how consistently students fill in the observation worksheet, using the pre-class troubleshooting observation as a control for all students. We also will consider how students' knowledge of both circuits and problem-solving skills, e.g., as measured using tools such as [8], [9], impacts their troubleshooting performance. Finally, we hope to assess troubleshooting in a larger variety of courses and map troubleshooting over the course of a 4-year undergraduate degree and explore what experiences help improve troubleshooting skills. This will involve creating similar activities to the ones presented here for other engineering disciplines and a variety of expertise levels.

6 Acknowledgments

Thank you to the students and TAs who helped to setup all the troubleshooting exercises and provided feedback on their design, to the reviewers for their helpful feedback, and especially to Gabriel McDerment for his help in developing the initial set of faulty circuits.

References

[1] L. D. Feisel and A. J. Rosa, "The Role of the Laboratory in Undergraduate Engineering Education," en, *Journal of Engineering Education*, vol. 94, no. 1, pp. 121–130, Jan. 2005, ISSN: 10694730. DOI: 10.1002/j.2168-9830.2005.tb00833.x.

[2] D. H. Jonassen and W. Hung, “Learning to Troubleshoot: A New Theory-Based Design Architecture,” en, *Educational Psychology Review*, vol. 18, no. 1, pp. 77–114, Mar. 2006, ISSN: 1040-726X, 1573-336X. DOI: 10.1007/s10648-006-9001-8.

[3] R. McCauley, S. Fitzgerald, G. Lewandowski, *et al.*, “Debugging: A review of the literature from an educational perspective,” en, *Computer Science Education*, vol. 18, no. 2, pp. 67–92, Jun. 2008, ISSN: 0899-3408, 1744-5175. DOI: 10.1080/08993400802114581.

[4] D. R. Dounas-Frazer and H. J. Lewandowski, “Nothing works the first time: An expert experimental physics epistemology,” en, in *2016 Physics Education Research Conference Proceedings*, Sacramento, CA: American Association of Physics Teachers, Dec. 2016, pp. 100–103. DOI: 10.1119/perc.2016.pr.020.

[5] K. L. Van De Bogart, D. R. Dounas-Frazer, H. J. Lewandowski, and M. R. Stetzer, “Investigating the role of socially mediated metacognition during collaborative troubleshooting of electric circuits,” en, *Physical Review Physics Education Research*, vol. 13, no. 2, p. 020 116, Sep. 2017, ISSN: 2469-9896. DOI: 10.1103/PhysRevPhysEducRes.13.020116.

[6] *Analog discovery 2*, Digilant. [Online]. Available: https://digilent.com/reference/test-and-measurement/analog-discovery-2/start.

[7] M. Kinsel, C. Crockett, N. Smith, and G. Prpich, “Circuit Troubleshooting Techniques in an Electrical and Computer Engineering Laboratory,” en, in *2024 ASEE Annual Conference & Exposition Proceedings*, Portland, Oregon: ASEE Conferences, Jun. 2024, p. 48 461. DOI: 10.18260/1-2--48461.

[8] D. R. Sokoloff, “Teaching Electric Circuit Concepts Using Microcomputer-Based Current/Voltage Probes,” en, in *Microcomputer–Based Labs: Educational Research and Standards*, R. F. Tinker, Ed., Berlin, Heidelberg: Springer Berlin Heidelberg, 1996, pp. 129–146, ISBN: 978-3-540-61558-3 978-3-642-61189-6. DOI: 10.1007/978-3-642-61189-6_7.

[9] P. P. Heppner and C. H. Petersen, “The development and implications of a personal problem-solving inventory.,” en, *Journal of Counseling Psychology*, vol. 29, no. 1, pp. 66–75, Jan. 1982, ISSN: 1939-2168, 0022-0167. DOI: 10.1037/0022-0167.29.1.66.

A Appendix A: Observation Protocol

The following is the first page of the observation protocol. The back side of the page contains steps 6-10 and the reflection questions: (1) Did the troubleshooter successfully reach the target circuit? (Yes, No) (2) What are your takeaways from this observation? Is there anything the troubleshooter did that you will use in future work? Is there anything that made the observation challenging?

Your name: ________________________ Circuit label: _____

Group member completing task:______________________

As your group member works on the circuit, record their actions. Use another step whenever there is a new train of thought or a new strategy. You may select multiple actions per step.

	Actions		Strategy	Notes
Step 1	☐ Using scope (note where) ☐ Referencing datasheet ☐ Reading schematic ☐ Visually inspecting circuit ☐ Tracing schematic/circuit ☐ Reasoning through the circuit ☐ Analytic calculations	☐ Makes a hypothesis ☐ Modify circuit: ☐ using hypothesis ☐ no clear rationale ☐ Other:	☐ Trial and error ☐ Consider alternatives ☐ Rebuild ☐ Tracing ☐ Isolation/split-half ☐ Output testing ☐ Gain domain knowledge ☐ Pattern matching	
Step 2	☐ Using scope (note where) ☐ Referencing datasheet ☐ Reading schematic ☐ Visually inspecting circuit ☐ Tracing schematic/circuit ☐ Reasoning through the circuit ☐ Analytic calculations	☐ Makes a hypothesis ☐ Modify circuit: ☐ using hypothesis ☐ no clear rationale ☐ Other:	☐ Trial and error ☐ Consider alternatives ☐ Rebuild ☐ Tracing ☐ Isolation/split-half ☐ Output testing ☐ Gain domain knowledge ☐ Pattern matching	
Step 3	☐ Using scope (note where) ☐ Referencing datasheet ☐ Reading schematic ☐ Visually inspecting circuit ☐ Tracing schematic/circuit ☐ Reasoning through the circuit ☐ Analytic calculations	☐ Makes a hypothesis ☐ Modify circuit: ☐ using hypothesis ☐ no clear rationale ☐ Other:	☐ Trial and error ☐ Consider alternatives ☐ Rebuild ☐ Tracing ☐ Isolation/split-half ☐ Output testing ☐ Gain domain knowledge ☐ Pattern matching	
Step 4	☐ Using scope (note where) ☐ Referencing datasheet ☐ Reading schematic ☐ Visually inspecting circuit ☐ Tracing schematic/circuit ☐ Reasoning through the circuit ☐ Analytic calculations	☐ Makes a hypothesis ☐ Modify circuit: ☐ using hypothesis ☐ no clear rationale ☐ Other:	☐ Trial and error ☐ Consider alternatives ☐ Rebuild ☐ Tracing ☐ Isolation/split-half ☐ Output testing ☐ Gain domain knowledge ☐ Pattern matching	
Step 5	☐ Using scope (note where) ☐ Referencing datasheet ☐ Reading schematic ☐ Visually inspecting circuit ☐ Tracing schematic/circuit ☐ Reasoning through the circuit ☐ Analytic calculations	☐ Makes a hypothesis ☐ Modify circuit: ☐ using hypothesis ☐ no clear rationale ☐ Other:	☐ Trial and error ☐ Consider alternatives ☐ Rebuild ☐ Tracing ☐ Isolation/split-half ☐ Output testing ☐ Gain domain knowledge ☐ Pattern matching	

B Appendix B: Example task sheets

The following are two example task sheets. The circuits are designed to be relatively simple and can be used near the middle or end of a first-semester circuits course or near the beginning of a follow-on electronics course.

Builder/observer name: ____________________________

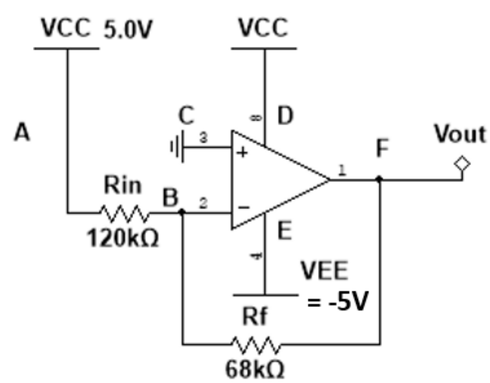
Troubleshooter name: ______________________

1. Build the circuit below on the second half of the page and verify that the output is correct. The output of the target circuit is -2.8V. This follows from the circuit being an inverting amplifier with an input of 5V and a gain of $-\frac{68}{120}$.
2. After confirming the output is reasonable (within tolerance), move the negative supply rail from -5V to ground (input pin 4 on the op amp). Now the op amp will rail and the output will stay around 0V. Verify this then fold this paper in half.
3. The troubleshooter should be able to see only the bottom half of this page while working!

------------------------ **FOLD HERE before giving this sheet to the troubleshooter** ------------------------

Your goal is to fix the provided circuit such that it matches the target circuit and expected output shown on right. Nodes are labeled in bold letters to help with any descriptions of process

Vout is -2.8V.



After the exercise is complete, answer the following questions:

How would you describe the approach you took to this task? Which troubleshooting strategies do you think you used?

Is there anything you would do differently next time?

Builder/observer name: ___________________________

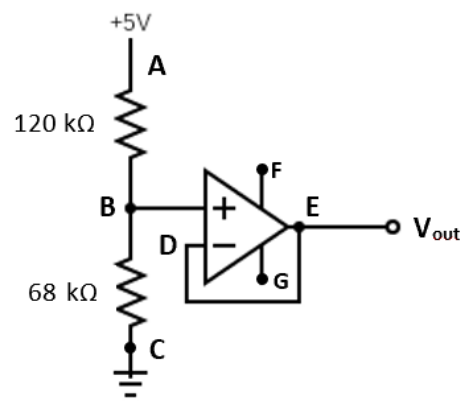
Troubleshooter name: ______________________

1. Build the circuit below on the second half of the page and verify that the output is correct. Note that Vout = $\frac{68}{68+120}5 = 1.8V$ because this circuit is a voltage divider followed by an op amp voltage follower.
2. After confirming the output is reasonable (within tolerance), swap the two resistor values. The new output should be Vout = $\frac{120}{68+120}5 = 3.2V$. Verify this then fold this paper in half.
3. The troubleshooter should be able to see only the bottom half of this page while working!

------------------------ **FOLD HERE before giving this sheet to the troubleshooter** ------------------------

Your goal is to fix the provided circuit such that it matches the target circuit and expected output shown on right. Nodes are labeled in bold letters to help with any descriptions of process.

Vout is 1.8V.



After the exercise is complete, answer the following questions:

How would you describe the approach you took to this task? Which troubleshooting strategies do you think you used?

Is there anything you would do differently next time?