Operational Amplifier Circuits: Non-Inverting Configuration and Electronic Voltmeter
ECE 2100 Circuit Analysis Laboratory
11 June 2021

Equipment and Supplies

<table>
<thead>
<tr>
<th>Item</th>
<th>Part Number</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Breadboard</td>
<td></td>
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<tr>
<td>Breadboard jumper wires</td>
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<tr>
<td>LTspice® program</td>
<td>Available</td>
<td><a href="https://www.jameco.com/products/ltspice">here</a></td>
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<tr>
<td>Ammeter Analog Current Panel Meter 50uA DC 60x47mm</td>
<td>Jameco #315301</td>
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<tr>
<td>Digital Multimeter (DMM)</td>
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<tr>
<td>Minigrabber to Stackable Banana Test Leads 24 AWG</td>
<td>Jameco #198731</td>
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<tr>
<td>Miniature Clip Test Leads 14&quot; 26AWG</td>
<td>Jameco #135299</td>
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<tr>
<td>(2) 9V battery holder with switch and hookup wires</td>
<td>Jameco #2128067</td>
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<tr>
<td>Small Phillips head screwdriver</td>
<td>Needed to install batteries</td>
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<tr>
<td>(2) 9V battery</td>
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<td>(3) 741 operational amplifier (2 spares)</td>
<td>Jameco #830522</td>
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<td>10kΩ 1/2W potentiometer</td>
<td>Jameco #2118791</td>
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<td>1kΩ 1/4W 5% resistor</td>
<td>From Jameco #10720 resistor kit</td>
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<td>2.2kΩ 1/4W 5% resistor</td>
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<tr>
<td>(3) 100kΩ 1/4W 5% resistor</td>
<td>From Jameco #10720 resistor kit</td>
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A resistor color code calculator like the one at

Learning Outcomes

Students will:
1. Use a breadboard to construct electric circuits;
2. Construct a non-inverting operational amplifier circuit and compare its calculated, simulated, and experimental DC Voltage Transfer Characteristic;
3. Construct an operational amplifier-based voltmeter using a meter movement in the feedback loop. This *active* design offers much improved performance over the *passive* design previously investigated.

Pre-Laboratory Assignment (STEPS 1-11)

1. **WASH YOUR HANDS** immediately after lab.
**Non-Inverting Amplifier**

2. Figure 1 shows an operational amplifier in a non-inverting amplifier configuration. This circuit is used in applications where the input voltage signal is too small and must be scaled without changing its shape. For example, Vin might originate from a microphone.

3. Compute the voltage gain Vout/Vin of this circuit. The variable resistor comprised of R3/R4 has no effect on the gain with Vin connected as shown.

4. Simulate the circuit DC Voltage Transfer Characteristic (VTC) using LTspice®.

   U1 is added to the schematic by selecting “opamp2” from the component library. Then right click on U1 and set “SpiceModel” and “Value” to LM741/NS.

   Download NationalSemicondcutorModels.lib from the course schedule. You **must** have that file in the same directory as your schematic file. That file defines the LM741/NS.

   You **must** have the statement “.include NationalSemiconductorModels.lib” on your schematic as a SPICE .inc directive (or as a SPICE directive depending on your version). This statement is added using the text tool. You can select SPICE .inc directive by right clicking the text box once placed on the schematic.

   Conduct a DC sweep of Vin: Simulate->Edit Simulation Command->DC sweep:

   Use a linear sweep from -4V to 4V in steps of 0.01V.

   LTspice® will compute Vout for each value of Vin.

   Since the simulation is at 0Hz frequency effects are ignored (thus the “DC”).

   Plot Vout versus Vin by running the simulation and placing the node voltage probe at Vout. This is the DC Voltage Transfer Characteristic. Your plot will look like Figure 2.

5. Determine the voltage gain by measuring the linear region slope. This is accomplished by a right click on the V(vout) plot symbol and using “Attached Cursor:”; “1st and 2nd”; then positioning the cursors in the linear region. Note that the two cursors are initially on top of each other and must be moved to see them. Compare the gain to the value computed in PreLab step 3.

6. Report calculated and simulated values of Vout in Table 1 for the indicated values of Vin. Simulated values may be obtained by using a cursor on your plot of PreLab step 5.

**Improved Voltmeter Design**

One drawback of the simple meter movement voltmeter constructed in the previous DC Meter Design Lab is its relatively low input resistance. Adding an op-amp results in a much-improved voltmeter (Figure 3). The beauty of this design is that the meter movement resistance is “hidden”
in the op-amp feedback loop.

7. Figure 3 shows a 5V full-scale meter movement-based voltmeter connected to measure node voltage \( V(\text{in}) \). The meter movement is modeled as a 2k\( \Omega \) resistor \( R_{\text{mm}} \). Determine the value of \( R_1 \) that results in \( I_{\text{mm}} = 50\mu A \) for \( V(\text{in}) = 5V \).

8. What was the problem measuring the voltage across a 100k\( \Omega \) resistor with your simple meter movement-based voltmeter (that used only a series resistance) in the previous Basic DC Meter Design lab?

9. Assuming an ideal op-amp, compute \( I_{\text{mm}} \) if \( V(\text{in}) = 5V \) (this ignores the effect of \( R_3 \) and \( R_4 \)). Does the value of \( I_{\text{mm}} \) make sense? Why?

10. What is the value of \( V(\text{in}) \) assuming an ideal op-amp (note \( R_3 \) and \( R_4 \) comprise a voltage divider since the non-inverting input of an ideal op-amp is an open)? What is the resulting value of \( I_{\text{mm}} \)?

11. Simulate the circuit as shown using LTspice®. Compare the value of \( V(\text{in}) \) and \( I_{\text{mm}} \) from simulation to hand calculations of PreLab step 10.

<table>
<thead>
<tr>
<th>( V_{\text{in}} ) (V)</th>
<th>( V_{\text{out}} ) (calculated)</th>
<th>( V_{\text{out}} ) (simulated)</th>
<th>% error sim (compare to calc)</th>
<th>( V_{\text{out}} ) (experimental)</th>
<th>% error exp (compare to calc)</th>
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<td>3.2</td>
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</table>

Table 1. Non-inverting amplifier performance data
Non-Inverting Voltage Amplifier

(c) 2020 Damon A. Hiller

U1 is a modified "opamp2" model
Put an "opamp2" instance on the schematic. Right click on opamp2.
Set "SpiceModel" and "Value" to LM741/NS

.lib NationalSemiconductorModels.lib
.dc Vin -4 4 0.01

Figure 1. Non-inverting operational amplifier circuit.
Small numbers next to U1 are pin numbers.

Figure 2. DC Voltage Transfer Characteristic of the circuit of Figure 1.
**Figure 3. Voltmeter based on an op-amp and meter movement.**

Small numbers next to U1 are pin numbers.

**Procedure**

**Non-inverting Amplifier**

1. TWO battery holders with an installed battery are required. For each battery holder: ENSURE THAT THE BATTERY HOLDER POWER SWITCH IS OFF and install a battery as needed.

2. Locate the resistors needed to construct the circuit of Figure 1. Measure each resistor to confirm its value.

3. The op-amp fits into the breadboard ACROSS THE BREADBOARD CHANNEL as shown in Figure 4. Note the location of pin 1 as denoted by the ‘dot’ marking on the op-amp (marked with red circle in Figure 4). The op-amp pins may be a little wide to directly insert the op-amp across the channel; thus, insert the bottom 4 pins first, then push the body with a slight pressure towards the bottom and insert the top 4 pins.

YOU MUST ORIENT THE OP-AMP PINS AS SHOWN, WITH PIN 1 ON THE BOTTOM LEFT.
The op-amp might fit loosely into the breadboard. **A LOOSE OP-AMP WILL NOT WORK.** Find a position where the op-amp fits securely into the breadboard.

4. Construct the circuit of Figure 1 as shown in Figure 4. Proceed as follows using Figure 4 as a guide.

Insert the battery holders leads as shown. V1 provides +9V. Its **red** lead is connected to VDC+. Its **black** lead is connected to ground. *The entire top breadboard row is VDC+ and is called the +9V positive supply rail.*

V2 provides -9V. Its **black** lead is connected to VDC-. Its **red** lead is connected to ground. The entire top breadboard row is VDC+. *The entire bottom breadboard row is VDC- and is called the -9V negative supply rail.*

*The second breadboard row from the bottom is the ground rail.*

Use a red wire to connect U1 pin 7 to the +9V supply rail (VDC+). Use a white wire to connect U1 pin 4 to the -9V supply rail (VDC-).

Connect R1 (1kΩ) between U1 pin 2 and the ground rail.

Connect R2 (2.2kΩ) between U1 pin 6 and U1 pin 2.

Resistor leads can be used as probes by connecting DMM test lead grabbers to them as in Figure 5. *****Alternatively, you can use a piece of hookup wire. This is preferred since **only the hookup wire ends are uninsulated.** In either case a resistor lead or wire attached to a DMM lead will be called a PROBE.*
Figure 4. Non-Inverting Op-Amp Circuit. Three resistors are used as probes for the ground, Vin, and Vout nodes.

Insert potentiometer R3/R4 into the breadboard as shown. Terminal a is connected to VDC(+) using a red wire. Terminal b is connected to U1 pin 3 using an orange wire. This is Vin. Terminal c is connected to U1 VDC(-) using a yellow wire. The inset image provides a different way to position the wires that better shows these connections.

Rotate the potentiometer shaft fully clockwise, then rotate the shaft counter-clockwise until the slot is as shown in the insert image. That centers the potentiometer setting.

**CAREFULLY REMOVE THE OP-AMP.**
5. Remove leads of both battery holders. Configure the DMM to read resistance.

6. Insert the red DMM (+) probe into the +9V (VDC+) supply rail. Insert the black DMM (-) probe into the ground rail. See Figure 5. The resistance must be greater than 20MΩ.

   *A lower resistance indicates improper wiring. Do not proceed until the resistance is correct.*

7. Insert the red DMM (+) probe into the -9V (VDC-) supply rail. Insert the black DMM (-) probe into the ground rail. The resistance must be greater than 20MΩ.

   *A lower resistance indicates improper wiring. Do not proceed until the resistance is correct.*

8. Insert the red DMM (+) probe into the +9V (VDC+) supply rail. Insert the black DMM (-) probe into the -9V (VDC-) supply rail. The resistance must be around 10kΩ.

   *A different resistance reading indicates improper wiring. Do not proceed until the resistance is correct.*

9. Remove the DMM probes. Reconnect leads of both battery holders. Verify battery connections via Figure 4. **Return DMM to a voltage measurement mode.**
10. Insert the red DMM (+) probe into the column where U1 pin 7 will be connected. This is VDC+ and at the end of a red wire. See Figure 6. Insert the black DMM (-) probe into the ground rail. Turn on power of both battery holders. The voltage must be around 9V. **TURN OFF BOTH BATTERY HOLDERS.** 

*An improper voltage reading indicates improper wiring. Do not proceed until the measurement is correct.*

![Image of multimeter and breadboard setup](image.png)

**Figure 6.** Measuring the positive and negative supply rail voltages at U1 pins 7 and 4, respectively.

11. Insert the red DMM (+) probe into the column where U1 pin 4 will be connected. This is VDC- and at the end of a white wire. See Figure 6. Insert the black DMM (-) probe into the ground rail. Turn on power of both battery holders. The voltage must be around -9V. **TURN OFF BOTH BATTERY HOLDERS.**

*An improper voltage reading indicates improper wiring. Do not proceed until the measurement is correct.*

12. Reinsert the op-amp into breadboard. **INSURE A TIGHT FIT AND VERIFY THAT PIN 1 IS AT THE BOTTOM AS SHOWN IN FIGURE 4.** The red VDC+ wire connects to U1 pin 7. The white VDC- wire connects to U1 pin 4. You can damage the op-amp if power is incorrectly connected.
13. Insert the red DMM (+) probe to the op-amp pin 3 column. This is node voltage $V_{in}$ and is set by the R3/R4 potentiometer. Insert the black DMM (-) lead into the ground rail. See Figure 7.

![Image of measurement setup](image)

Figure 7. Measurement of $V_{in}=1.89V$ (left) and $V_{out}=6.05V$ (right). The gain is 3.2V/V.

14. Note there are two battery holders to turn off and on. It is important that they both be turned on and off at about the same time. Turning one off (on) then immediately turning the other off (on) is sufficient.

15. Double check connections one more time.
   - Turn on both battery holders.
   - Rotate potentiometer R3/R4 until $V_{in}$ is about 0V.
   - **TURN OFF BOTH BATTERY HOLDERS.**

16. Insert the red DMM (+) probe into op-amp pin 6 column. See Figure 7. This is node voltage $V_{out}$.
   - Turn on both battery holders.
   - Measure $V_{out}$.
   - **TURN OFF BOTH BATTERY HOLDERS.**

17. $V_{out}$ should be about 0V. If it is not your circuit is not working. Here are some debugging steps to perform before contacting your instructor:
   a. Connect red DMM (+) probe grabber to op-amp pin 7 column.
      - Turn on both battery holders. The voltage should be about 9V.
      - **TURN OFF BOTH BATTERY HOLDERS.**

   b. Connect red DMM (+) probe grabber to op-amp pin 4 column.
      - Turn on both battery holders. The voltage should be about -9V.
      - **TURN OFF BOTH BATTERY HOLDERS.**

   c. Connect red DMM (+) probe grabber to op-amp pin 2 column,
Turn on both battery holders. Measure and record voltage Vpin2.
**TURN OFF BOTH BATTERY HOLDERS.**

d. Connect red DMM (+) probe grabber to op-amp pin 3 column. 
   Turn on both battery holders. Measure and record voltage Vpin3.
   **TURN OFF BOTH BATTERY HOLDERS.**

e. If the op-amp is in the linear region then Vpin2=Vpin3 due to negative feedback. 
   If this is not the case ensure that the feedback resistor R2 is connected to the correct pins.

18. Once your circuit is working complete the following steps. 
   **IT DOES NOT MAKE SENSE TO CONTINUE** if your circuit is not working.

19. For each value of Vin in Table 1:

   a. Connect red DMM (+) probe to Vin (U1 pin 3 column). See Figure 7. 
      Turn on both battery holders. 
      Adjust the potentiometer to the desired Vin. *Record Vin.*
      **TURN OFF BOTH BATTERY HOLDERS.**

   b. Connect red DMM (+) probe to Vout (U1 pin 6 column). See Figure 7. 
      Turn on both battery holders. 
      Measure and record Vout. 
      **TURN OFF BOTH BATTERY HOLDERS.**

20. Update Table 1 with your actual values of Vin, Then update the calculated and simulated 
    values of Vout for those values of Vin. Compute the indicated errors.

21. *Do not disassemble your circuit. You will use the circuit in the next section.* 
    If the errors between your measured and calculated values are small, then continue to the 
    next circuit. If not, seek help from your instructor.

**Improved Voltmeter**

The non-inverting configuration is readily modified to act as a voltmeter by replacing R2 with 
the meter movement and R1 with a resistor that yields the full-scale meter movement current for 
the desired full-scale voltmeter voltage.

22. **ENSURE BOTH BATTERY HOLDERS ARE OFF.**

23. Replace R1 with the resistor computed in PreLab step 7 as shown in Figure 8. 
    *Your value of R1 might be different.*

24. Remove the potentiometer and connect R3=100kΩ and R4=100kΩ as shown in Figure 8.

25. Replace R2 with the DMM configured as an ammeter as shown in Figure 8. **NOTE THE** 
    DMM POLARITY. We will use the DMM to verify the proper current before using the meter 
    movement.
26. Turn on both battery holders.
   Verify that the DMM is current is about 50\,\mu A.
   **TURN OFF BOTH BATTERY HOLDERS.**
   **Configure the DMM as a voltmeter.**

   An improper current reading indicates that the circuit is not working. Do not proceed until the measurement is correct.

27. Replace R2 with the meter movement as shown in Figure 9. **NOTE THE METER MOVEMENT POLARITY.** The red grabber is connected to the meter movement (+) terminal and the black grabber is connected to the meter movement (-) terminal.

   **PUT A SHORT ACROSS THE METER MOVEMENT** (see Figure 9). This protects the meter movement during the power on/power off transient.
Figure 9. Op-Amp Voltmeter. The op-amp voltmeter reads $V_{in} = \frac{46 \mu A}{50 \mu A} \times 5V = 4.6V$ The DMM reads 4.68V.

Red curve shows where to place meter movement protection jumper. You can use a wire to connect U1 pins 2 and 6 or connect a minigrabber jumper where the meter leads are attached.
28. Configure the DMM as a voltmeter.
   Connect red DMM (+) probe to U1 pin 3.
   This is the node voltage Vin measured by the voltmeter.

29. Turn on both battery holders.
   Record DMM voltage Vin.
   Remove the meter movement short.
   Record the meter movement current. The voltage reading is obtained by dividing that current by 50µA and multiplying by 5V (the full-scale voltmeter voltage).

**PUT A SHORT ACROSS THE METER MOVEMENT.**
   This protects the meter movement during the power on/power off transient.

**TURN OFF BOTH BATTERY HOLDERS.**
   The readings should be in close agreement.
   If not, consult with your instructor.
   Do not disassemble your circuit until your results make sense.

30. Disassemble the circuit and stow away components. Be sure that your DMM is in a voltage measurement mode and is OFF.

31. Ensure that the battery holder leads and battery terminals will not be inadvertently connected together by wires, metallic tools, etc. during storage.

32. Wash your hands when done.

**Clean-Up**

33. Wash your hands after lab.

**Analysis**

1. Compute the average error between simulated and calculated Vout results and between experimental and calculated Vout results in the LINEAR REGION for the data of Table 1.
   Comment on results.

2. Compute the average error between simulation and calculated Vout results and between experimental and calculated Vout results in the SATURATION REGIONS for the data of Table 1. Comment on results.

3. Does the meter movement resistance Rmm affect its current in the op-amp voltmeter of Figure 3?

4. Explain why the op-amp voltmeter was able to accurately measure the voltage across the 100k resistor in Figure 3 while the simple voltmeter of the Basic DC Meter lab was not.
Credits and Copyright

Adapted from material developed by current and former ECE faculty, including J. Kelemen and F. Severance. Modified based on input from ECE laboratory instructors, particularly S. Masihi, M. Panahi, M. El Yabroudi, and S. Hajian. S. Durbin contributed to the development of this laboratory.

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