Name: ____

Date of lab: ______________________ Section number: M E 345.______

Lab 7

Precalculations – Individual Portion
Op-Amp Lab: Operational Amplifier Circuits

Precalculations Score (for instructor or TA use only):	_____ / 20

1. **(7)** Suppose a bunch of 10-kohm resistors are available in the lab. A powered breadboard with DC voltage power supplies of +15 V and –15 V is available, along with a ground post (0 V). Several type 741 op-amps, some switching diodes, and +5 V and –5 V power supplies are also available. Draw a circuit diagram showing how an ***inverting amplifier*** with a gain of –1.5 can be constructed with these components only. Use the standard triangle symbol for the op-amp(s), and label the inputs V_n and V_p.

2. **(6)** For the above example, draw a rectangle to represent the 8-pin integrated circuit for the type 741 op-amp. Label all eight pins (1 to 8), and draw lines to show how the pins would be wired on a breadboard to create the inverting amplifier of Question 1. Be sure to include the supply voltages!

3. **(7)** For the same list of components as in Question 1, draw a circuit diagram that clips voltages below –5 V, and clips voltages above +5 V.

Lab 7

Cover Page for

Lab Report – Group Portion

Op-Amp Lab: Operational Amplifier Circuits

Name 1: ____ Section M E 345.______

Name 2: ____ Section M E 345.______

Name 3: ____ Section M E 345.______

[Name 4: ____ Section M E 345.______]

Date when the lab was performed: ____________________

Group Lab Report Score (For instructor or TA use only):

Lab experiment and results, plots, tables, etc.	_____ / 50
Discussion	_____ / 30
TOTAL	**_____ / 80**

Lab Participation Grade and Deductions – The instructor or TA reserves the right to deduct points for any of the following, either for all group members or for individual students:

- Arriving late to lab or leaving before your lab group is finished.
- Not participating in the work of your lab group (freeloading).
- Causing distractions, arguing, or not paying attention during lab.
- Not following the rules about formatting plots and tables.
- Grammatical errors in your lab report.
- Sloppy or illegible writing or plots (lack of neatness) in your lab report.
- Other (at the discretion of the instructor or TA).

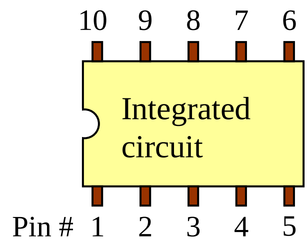
Name	Reason for deduction	Points deducted	Total grade (out of 80)

Comments (for instructor or TA use only):

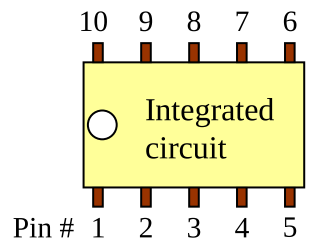
Op-Amp Lab: Operational Amplifier Circuits

Author: John M. Cimbala; also edited by Mikhail Gordin and Savas Yavuzkurt, Penn State University
Latest revision: 18 October 2013

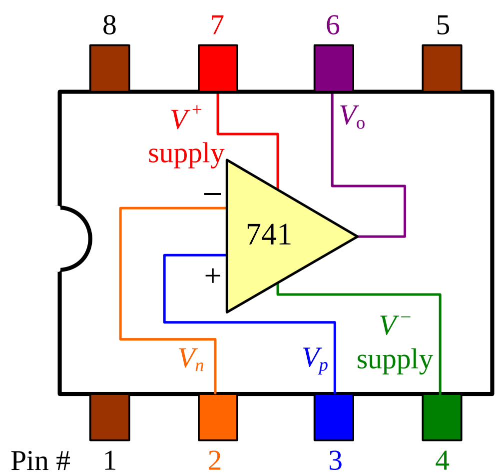
Introduction and Background (*Note*: To save paper, you do *not* need to print this section for your lab report.)
An ***operational amplifier*** (usually abbreviated ***op-amp***) is an integrated circuit that amplifies the difference in voltage signal across its input terminals. In a so-called ***open-loop configuration***, without feedback, the output is some multiple (the ***open loop gain g***) of the difference between the two input voltages, $\boxed{V_o = g\left(V_p - V_n\right)}$. The open loop gain is typically in the 10^5 or 10^6 range, and thus the op-amp easily ***saturates***, even for very small input voltages. In practice, most circuits are built with a ***feedback loop*** (***closed-loop configuration***), so that the voltage difference between the negative and positive input terminals is negligible. Some practical circuits which utilize op-amps are presented in the Op-Amps learning module. In this lab, some of these circuits are built and tested on a breadboard. Then, as a practical application, the circuits are used to measure the frequency range of students whistling. In this lab, the industry standard type 741 op-amp is used.



It is critical that you know how the pins on an IC are numbered. By convention, the pin numbers start (starting at pin number 1) at the *lower left* of the chip, and proceed *counterclockwise* around the chip. Lower left is defined properly when the IC is oriented with the small semi-circle or notch to the left, as sketched above right or sometimes with an indented circle, as sketched below right. The sketches show how the pins are numbered for a 10-pin IC when viewed from the top (pins pointed into the page). When oriented properly, the numbers and letters painted on the chip should also read from left to right, but this is not always reliable – *it is best to orient the IC based on the notch or the circle rather than on the printed labels on the chip surface*.



The 741 op-amp is an 8-pin IC. The schematic diagram to the right shows the pin connections for the 741 op-amp. The pins are color coded; this will be useful in the lab procedure. Pins 7 and 4 must be supplied with the positive and negative power supply voltage, respectively, typically +15 and –15 V. [*Be sure to connect these power supply voltages, or the op-amp will not work!*] Pin 2 is the negative or inverting input terminal V_n, and pin 3 is the positive or noninverting input terminal V_p. Pin 6 is the op-amp output V_o. Pins 1 and 5 enable you to adjust the offset null, but are not used in this lab. Pin 8 is not connected to anything.



Objectives

1. Practice wiring integrated circuits to a breadboard.
2. Construct and test several op-amp circuits, including a noninverting buffer, inverting summer, inverter, and inverting amplifier.
3. Construct a circuit to amplify the voltage signal from a function generator, and then play the tone through a speaker.

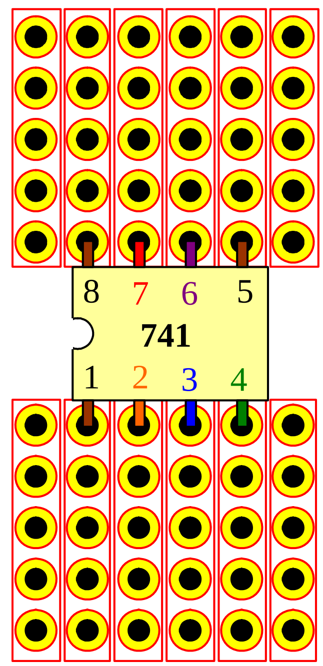
Equipment

- resistors (4 120-ohm resistors, 2 2-kohm resistors, 1 10-kohm resistor, 1 5-to-20-ohm potentiometer)
- cables (alligator, test lead, BNC, banana) and connectors (tees, etc.), as required
- decade resistance box
- 3 type 741 op-amps
- 8-ohm speaker
- powered breadboard and jumper wires for breadboarding
- function generator
- digital multimeter (DMM)
- digital oscilloscope
- personal computer with digital data acquisition software

Procedure

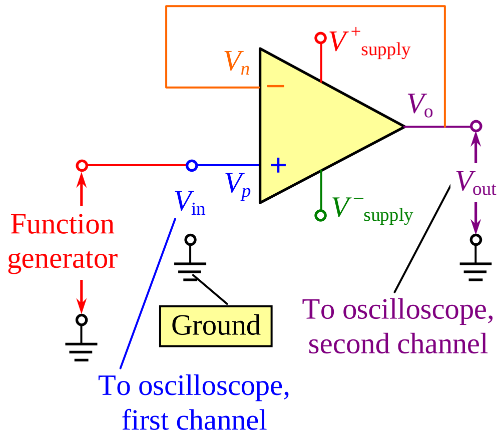
Set-up of breadboard, function generator, and oscilloscope

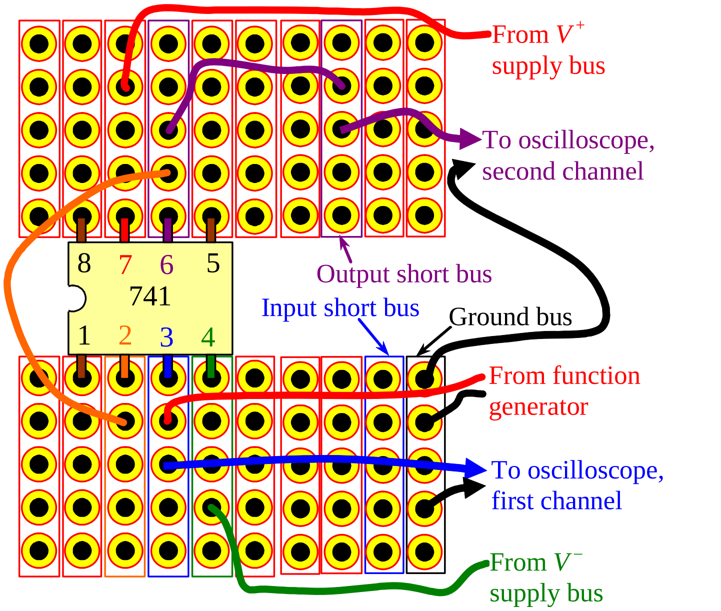
1. Plug in and set up the powered breadboard such that it is easily visible and accessible by each student in the group. ***To avoid possible short circuits, always turn off the breadboard power supply while building or modifying circuits***.
2. Choose one of the long buses as the ground bus. Connect the breadboard ground (the black post at the top) to the ground bus, and make sure the breadboard is plugged in so that you have a good ground bus.
3. Similarly, choose and wire another long bus as the +15 V power supply bus.
4. Similarly, choose and wire a third long bus as the –15 V power supply bus.
5. *Note*: It is wise to establish a color code for your wiring, in order to avoid confusion later. In this document, all ground wires are black, all +15 V wires are red, all –15 V wires are green, etc. **Please follow the same color convention so that troubleshooting your circuits is easier.**
6. Using a BNC tee and a BNC-to-alligator clip cable, connect the function generator output to one channel of the oscilloscope. Also connect the function generator signal output (red lead) to a short bus on the breadboard. From now on, this short bus will be called the ***input short bus***. Connect the ground of the cable (black lead) to the ground bus.
7. Turn on the function generator and study the signal on the oscilloscope. Adjust the amplitude and frequency of the function generator such that a sine wave of approximately 100 Hz, with peak-to-peak amplitude around 5 V (±2.5 V), is generated. Adjust the amplitude and time settings of the oscilloscope appropriately so that a couple periods of the sine wave are clearly visible.
8. Set the DC offset button on the function generator to zero (usually by pushing the button in, but on some function generators by pulling the button out). This will remove any DC offset from the input signal. Verify this.
9. Choose another short bus as the ***output short bus***, and similarly wire from the output short bus to the *second* working channel of the oscilloscope. Don't forget to also wire the ground (black lead) of the BNC-to-alligator cable to the ground bus. Now the breadboard is ready for building circuits.
10. *Note*: Make sure both working channels of the oscilloscope are set to DC Coupling. (Use the Menu button to select between DC and AC coupling.)
11. Insert an op-amp into the breadboard such that the lower four pins (1 to 4) are connected to four separate short buses, and the upper four pins (5 to 8) are connected to four *different* short buses. This is accomplished by *straddling* the op-amp between rows of short buses as sketched to the right – breadboards are designed to easily accommodate standard ICs. *Be careful not to bend the leads of the op-amp as you push it into place.*



Noninverting Buffer

1. For the first circuit, connect the jumper cables to form a simple ***noninverting buffer***. Both the schematic diagram and a sketch of one possible breadboard circuit are shown below; the wires are color coded for your convenience. The input short bus and output short bus are labeled. The short buses in this diagram run vertically, each with five sockets per bus. *Don't forget to connect the grounds (black leads) on your cables, or your voltage signal will not be displayed properly on the oscilloscope*.
2. Turn *on* the breadboard power supply. If everything is wired correctly, the output should be identical to the input. Verify this with the two channels of the oscilloscope. ***The purpose of a buffer is not to change the signal, but rather to provide the input signal with a high impedance, so that the input signal is not affected by any circuit components downstream.*** *Note*: If the circuit does not work, the usual problem is lack of connection(s) to ground. Check all your wiring with the breadboard off, and then try again.
3. *Note*: If the output is not equal to the input, and/or if the op-amp gets hot to the touch, you have most likely wired something incorrectly. If this is the case, turn off the breadboard power supply immediately to avoid burning out the op-amp or damaging the equipment.



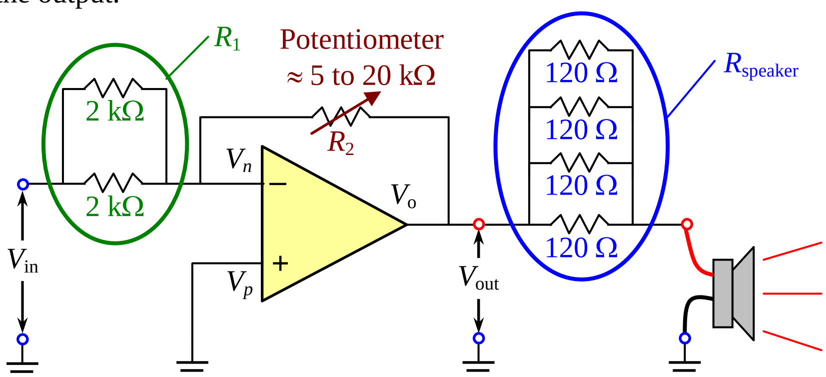


Note: Make sure the ground bus is properly grounded to the ground post on breadboard.

4. **(5)** In the space below, summarize your observations – does the buffer do what it is supposed to do?

Powering a speaker with an op-amp amplifier

1. Turn *off* the breadboard power supply while modifying the circuit.
2. On another part of the breadboard, and using a second op-amp, create an ***inverting amplifier***, which amplifies input voltage V_{in} and inverts the output.
   - Use the two 2-kohm resistors in parallel to create a 1-kohm resistor for R_1.
   - Use the potentiometer as R_2. Note that pins 1 and 6 of the potentiometer (the two outermost pins) are used – ignore the other pins of the potentiometer. Turn the knob to about half way.
   - Don't forget to *power* to the second op-amp – it needs both +15 V and –15 V power, or it will not work.



3. Wire the output from the function generator to voltage, V_{in} of your inverting amplifier. Set the function generator to a frequency of around 2 kHz with an amplitude around 0.5 V (500 mV), or as low as possible if your function generator can not reach 0.5 V.
4. The output of the amplifier will power the speaker. However, the speaker has a resistance of about 8 ohms, which is too low – it would draw too much power from the op-amp. So, we first send the output voltage from the amplifier to a 30-ohm resistor in series with the speaker as sketched. To create a 30-ohm resistor, wire the four 120-ohm resistors in parallel as sketched above.
5. Connect the speaker (**red wire** in series with the 30-ohm resistor and **black wire** to ground, as sketched).
6. Turn on the breadboard power supply. You should hear a tone corresponding to the input frequency.

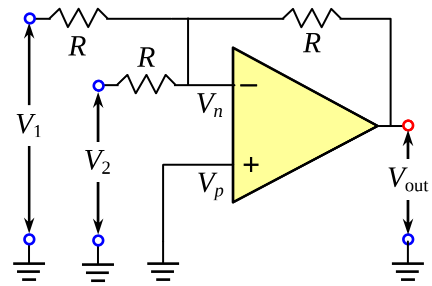
7. **(5)** Adjust the potentiometer knob to control the volume. Adjust the frequency to hear various tones. In the space below, summarize your observations. [Normal healthy human hearing is 20 Hz to 20 kHz.]

8. **(2)** Record the minimum and maximum frequencies that a lab group member can hear from the speaker.

   Name: ___________________________ Minimum *f* = ___________ Hz. Maximum *f* = ___________ Hz

Note: What you have just built is a crude amplifier, such as what is used in stereo systems. If you used a more powerful op-amp (called a power op-amp) and a better speaker, you would hear much better sound quality.

Inverting summer



1. Turn *off* the breadboard power supply while modifying the circuit.
2. On another part of the breadboard, and using the third op-amp, create an ***inverting summer*** (sketched to the right) which adds two voltages V_1 and V_2, and inverts that sum. Use 10-kohm resistors.
3. Connect the function generator output to your noninverting buffer (previously built). Wire the output from the noninverting buffer to the first voltage V_1 of your inverting summer.
4. Wire +5 V (use the 5 V power supply that is supplied by the breadboard, if available) to the second voltage V_2 of your inverting summer. (*Note*: If you are using a separate 5 V power supply, you need to connect the ground from the second power supply output to your ground bus – otherwise, the 5 V signal from the second power supply will "float" and not work properly.)
5. Don't forget to *power* the third op-amp – it needs both +15 V and –15 V power.
6. Change the wiring so that the output from this inverting summer goes to the second working channel of the scope. *Caution: Make sure only one output at a time is connected to a given channel of the oscilloscope. If you connect two different outputs to the same oscilloscope input, you can damage the equipment.*
7. **(5)** Turn on the breadboard power and observe the two signals on the scope. Are the two voltage signals added as expected? Record the results below, including a sketch of the two oscilloscope channels. *Note:* You should measure each separately from the others; turn off the other channel, leaving just the one you wish to measure active, and ***autoset*** the oscilloscope on that active channel. Then repeat this with the remaining channel. This will give you more accurate results.

Inverter

1. Remove the 5 V signal, which was called V_2 above.
2. Remove the resistor that was connected to that signal. The circuit is now a simple ***inverter***.
3. **(5)** Verify that this is indeed an inverter, and draw a sketch of the two oscilloscope channels in the space below.

Inverting amplifier – Measuring the amplifier behavior as a function of input frequency

1. Modify the circuit that uses the third op-amp to create an ***inverting amplifier*** as follows:
2. A 10-kohm resistor should already be in place for the resistor labeled R_1 in the learning module (inverting amplifier). Replace the feedback loop resistor (which is labeled R_2 in the learning module) with the decade resistance box, so that the gain of the amplifier can be easily adjusted.
3. **(2)** Set the decade resistor so that the gain of the inverting amplifier is –10. Record the values of R_1 and R_2.

Inverting amplifier resistance, R_1 = ____________ Ω

Inverting amplifier resistance, R_2 = ____________ Ω

4. Verify that the output of the noninverting buffer is still connected to the input of the inverting amplifier and to the first working channel of the oscilloscope, and that the output from the inverting amplifier is still connected to the second working channel of the oscilloscope.
5. **(4)** Use the function generator as the input voltage. Start with a frequency around 10 Hz with a peak-to-peak amplitude of 1 V (+/- 0.5 V). At G = –10, the amplifier output should have a peak-to-peak amplitude of 10 V (+/- 5V). Verify this. Show your calculations below, and enter your results in the table below.

Frequency	**Measured peak-to-peak amplitudes**		**Gain**	
f **(Hz)**	**Input (volts)**	**Output (volts)**	**Theoretical**	**Measured**
10				

6. **(10)** Generate a table (it is recommended that you use Excel for this) with the same columns as the table above. Determine and record the peak-to-peak amplitudes of the *input* (from the function generator) and *output* (from the inverting amplifier output) as functions of frequency ranging from 10 Hz to as high a frequency that you can generate with the function generator. For each frequency, calculate the theoretical gain and the measured (experimental or actual) gain, and compare. *Note*: For best results, increase frequency *logarithmically*, as in the filter lab, e.g., 10, 20, 40, 75, 100, 200, … etc. Print and attach your table.

See attached Table ____________ .

7. **(5)** Does the gain of your inverting amplifier change with input frequency? Discuss. What is happening here?

8. **(5)** Set the input signal to a 100 Hz sine wave of amplitude around 5 V peak-to-peak [*Note*: On some function generators, you may need to push in or pull out the amplitude knob to make it functional.] Make sure the gain of the amplifier circuit still set to –10. Draw a sketch of the two oscilloscope traces.

What is happening here? Explain.

9. **(2)** Based on your observations, what are the minimum and maximum ***saturation voltages*** of the op-amp?

Minimum (negative) saturation voltage of the op-amp, $V_{\text{negative saturation}}$ = ____________ V

Maximum (positive) saturation voltage of the op-amp, $V_{\text{positive saturation}}$ = ____________ V

Discussion Questions

1. **(5)** What is the range of frequencies that could be heard by the lab group member? Calculate his/her ***dynamic range*** (dynamic range is defined as the difference between the highest and lowest frequency). Compare to the normal "healthy" dynamic range for young persons, which is 20 to 20,000 Hz.

2. **(5)** What is the purpose of a buffer, and when might a buffer be useful?

3. **(5)** With simple op-amp circuits like those built here, is it possible to amplify a signal to a voltage greater than the positive supply voltage (e.g., 15V) supplied to the op-amp? Explain.

4. **(15)** Write a short summary of the usefulness of op-amps. In particular, name some practical applications of op-amps in commonly used devices and equipment. You may use the Internet to help you find some examples.