LAB EXPERIMENTS USING NI ELVIS II AND NI MULTISIM

Alexander Ganago
Jason Lee Sleight

University of Michigan
Ann Arbor

Lab 4
Operational Amplifiers (Op Amps)

Goals for Lab 4

- Learn about operational amplifiers (op amps):
    - 5 terminals of an op amp chip
    - Connections to the power supply
    - The "Golden Rules" (GRs) used to calculate the gain of amplifier circuits
    - Clipping of output signals in amplifier circuits
    - Phase shifts between the input and output signals in amplifier circuits
- Learn about inverting and noninverting amplifier circuits with fixed and variable gain based on op amps:
    - in the pre-lab, model these circuits
    - in the lab, build them and measure input and output signals
    - in the post-lab, compare the results of your modeling with your lab data; draw conclusions on the agreement/disagreement between theory and experiment
- Learn about the Gain*Bandwidth (G*BW) product:
    - In pre-lab, calculate it for LM 741 and LF 356 from the manufacturer's specifications
    - In the lab, measure amplifier gain over a broad range of frequencies
    - In the post-lab, compare your pre-lab calculations with your lab data; draw conclusions on their agreement/disagreement
- Learn about the buffer, or voltage follower and its significance
    - in the pre-lab, model these circuits
    - in the lab, build them and do the measurements of output signals
    - in the post-lab, compare the results of your modeling with your lab data; draw conclusions on the agreement/disagreement between theory and experiment
- Explore (for extra credit) the clipping conditions for output signals in op amp circuits
    - in the pre-lab, calculate the clipping from manufacturer's specifications
    - in the lab, measure the clipping of output signals in your amplifier circuit
    - in the post-lab, compare the results of your modeling with your lab data; draw conclusions on the agreement/disagreement between what you expected from the specs and what you found in your experiments
- Explore (for extra credit) phase shifts between the input and output signals in amplifier circuits
    - in the pre-lab, learn to relate the shifts in degrees to the shifts in μs
    - in the lab, measure the shifts in μs
    - in the post-lab, compare the results of your measurements in μs with automatic measurements in degrees.

Introduction

Operational amplifiers (op amps) are integrated circuits (ICs) used in many applications. In this lab, you will build and study several amplifiers based on two different op amp chips. Many op amp chips are on the market; do a Google search to learn more if you wish.

Although the internal circuitry of an op amp is quite complex, using op amps in circuits is very simple. You have to know just a few facts in order to begin.

Op Amp Terminals

A typical op amp chip has at least 5 terminals as shown in Figure 4-1:

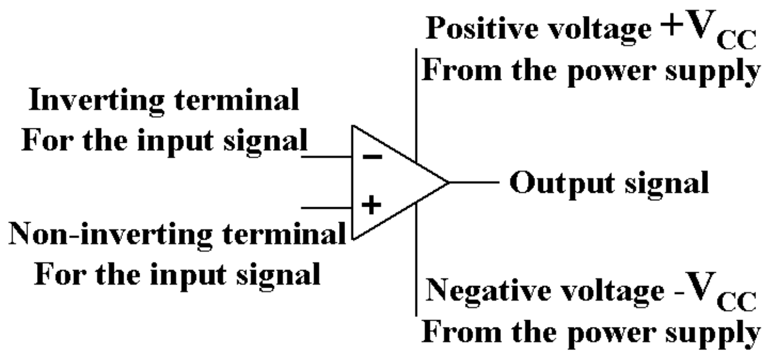


Figure 4-1. Op amp terminals.

- Two terminals for input signals: inverting (labeled –) and noninverting (labeled +)
- A terminal for the output signal, and
- Two terminals for the power supply voltages: positive $+V_{CC}$ and negative $-V_{CC}$.

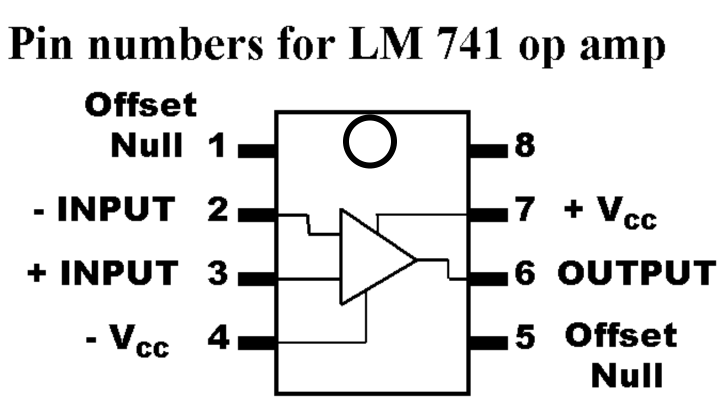


Figure 4-2. Pin numbers for LM 741 op amp [dual-in-line package (DIP)].

In the lab you will use LM 741, the classic op amp chip whose pin numbers are shown in Figure 4-2. Pin numbers for other types of op amp chips can be the same (for example, a newer op amp LF 356 that can replace LM 741), which makes replacement of chips very simple, or totally different (for example, LM 386—a power output amplifier, which cannot be used as a direct replacement for LM 741). In the lab, you will use LF 356 as a direct replacement for LM 741 and do measurements to compare the performance of the two chips.

The op amp chip in a DIP package looks like a small rectangle with 8 pins; the circle shown in Figure 4-2 is impressed on each chip to denote pin #1. Note that pin #8 is not connected; pins #1 and #5 are not used in this lab.

In some circuits (such as differential or instrumentation amplifiers), both input terminals are connected to input signals; in other circuits only one terminal is used for the input signal; then the other input terminal is connected to the ground.

Note that without connections to the power supply (terminals labeled $+\mathbf{V_{CC}}$ and $-\mathbf{V_{CC}}$) your op amp circuit will not work, as your car will not run without gas. Be careful, because these connections are implied and not shown on many circuit diagrams. Do not mistake the connections of input signals (labeled – and +) for the connections to the power supply ($+\mathbf{V_{CC}}$ and $-\mathbf{V_{CC}}$).

Connections to the Power Supply

Many op amp chips require both positive and negative voltages from the power supply as shown in Figure 4-3. The power supply should have separate terminals for the positive and negative voltages. In this lab you will connect LM 741 (or LF 356) to +12 V (pin #7) and to –12 V (pin #4).

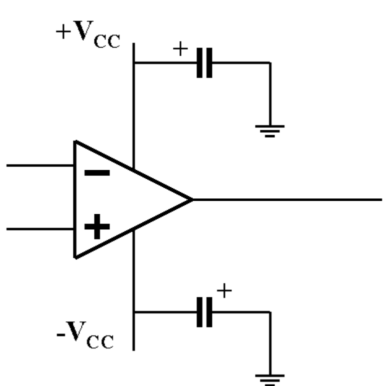


Figure 4-3. Connections of an op amp to the power supply.

When you build your circuit, connect large electrolytic capacitors (such as 220 μF or 470 μF) between each power supply rail and the ground, as shown in Figure 4-3. These capacitors are needed to stabilize your circuit and to avoid “humming” of your audio amplifiers due to the ripple voltages from the power supply.

Warning: The polarity is important: an electrolytic capacitor can explode if its positive terminal is connected to a negative DC voltage.

The Gain of Amplifier Circuits

The amplifier circuits are characterized by their gain values. The voltage gain (which is often called simply "gain") is the ratio of output voltage to the input voltage in the circuit:

$$\text{Voltage Gain} = \frac{\text{Output Voltage}}{\text{Input Voltage}}$$

The amplifier gain is a special case of a circuit's transfer function, about which you will learn when you work with filters.

Think about two families of amplifiers:

- Noninverting, in which the output signal has the same sign as the input, and
- Inverting, in which the output signal has opposite sign, as sketched in Figure 4-4.

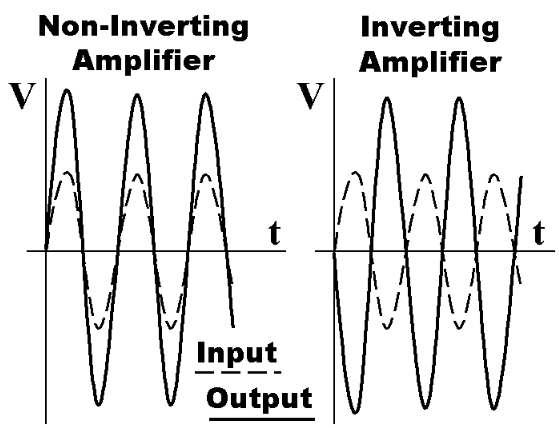


Figure 4-4. Input and output voltages of noninverting and inverting amplifiers.

The gain of noninverting amplifiers is positive; the inverting amplifiers' gain is negative. Each family of amplifiers has its advantages; both families are widely used.

In the lab, your oscilloscope can measure peak-to-peak amplitudes of signals in two channels, to which you will connect the input and the output signals of your amplifier at the same time. Record both amplitudes and calculate the gain magnitude:

$$\left|\text{Gain}\right| = \frac{\text{Output Voltage (peak-to-peak)}}{\text{Input Voltage (peak-to-peak)}}$$

In many applications, the magnitude of the gain is more important than its sign.

We can also express the magnitude of the gain on the logarithmic scale using decibels:

$$\text{Gain in dB} = 20 \cdot \log_{10}\left(\frac{\text{Output Voltage (peak-to-peak)}}{\text{Input Voltage (peak-to-peak)}}\right)$$

Gain in dB is positive if |Gain| > 1, negative if |Gain| < 1, and zero if |Gain| = 1.

Resistors Determine the Gain of Amplifier Circuits

In amplifier circuits, the inverting input terminal is connected to the output terminal (see resistor R_F in Figure 4-5); this is called negative feedback loop.

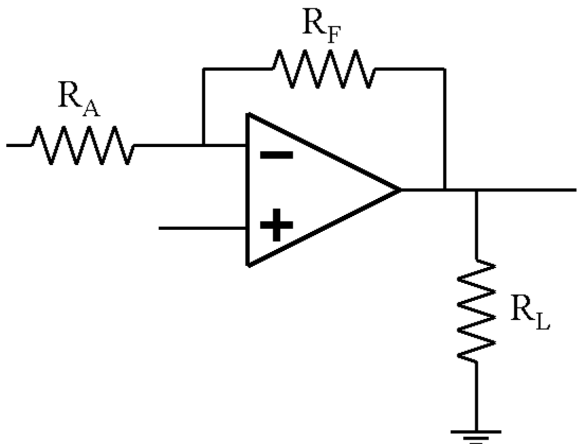


Figure 4-5. Resistor R_F serves as a negative feedback loop in op amp amplifier circuits.

The gain of amplifier circuits is determined by the resistors connected to the op amp chip (not by the chip itself). In particular, the ratio $\frac{R_F}{R_A}$ of the feedback resistor R_F and the input resistor R_A determines the gain of simple circuits, which you build in this lab. Ideal op amps (which exist only in textbooks) operate regardless of the load resistor R_L but in practical amplifier circuits this resistor is important.

The circuit diagram in Figure 4-5 serves as a backbone for building both noninverting and inverting amplifiers. However, this diagram is incomplete: it does not show how the input op amp terminals are connected to the sources of signals and to the ground.

Let us consider several specific, practical circuits.

How to Build a Noninverting Amplifier

The circuit diagram of a basic noninverting amplifier is very simple: in addition to the op amp chip, it has only 3 resistors as shown in Figure 4-6.

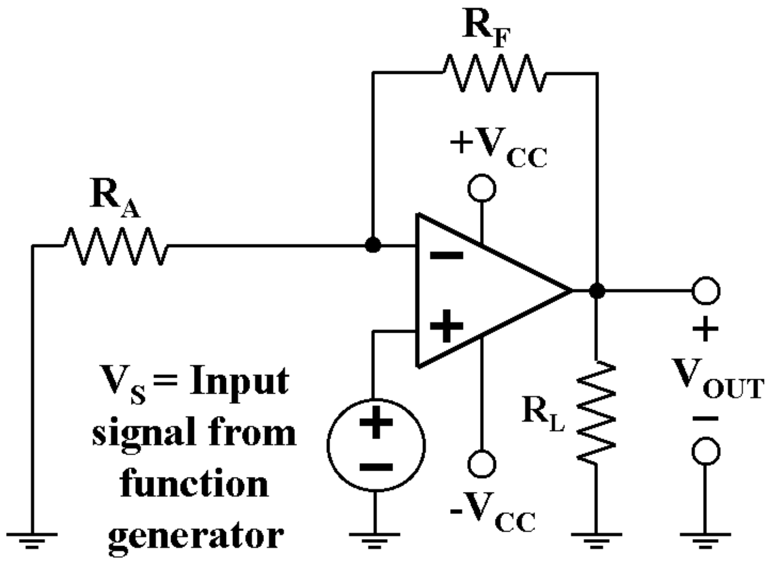


Figure 4-6. Basic noninverting amplifier.

Warning: Notice that the capacitors in the bus lines $+V_{CC}$ and $-V_{CC}$ are not shown for simplicity but they are of course necessary.

To build this noninverting amplifier, connect the input signal directly to the noninverting input terminal of your op amp chip. Connect the inverting input to the ground through the input resistor R_A.

Warning: Do not connect the inverting input of your op amp directly to the ground: your amplifier circuit must have the resistor R_A (see the note below).

The noninverting amplifier's gain is easy to derive from the node voltage equation at the inverting input terminal and the so-called GRs for an ideal op amp.

$$V_+ = V_S \text{ due to connection}$$
$$V_- = V_+ \text{ due to the GR}$$
$$\frac{V_- - 0}{R_A} + \frac{V_- - V_{output}}{R_F} + i_- = 0; \text{ neglect } i_- \text{ due to GR}$$
$$\text{Thus, Gain} = \frac{V_{output}}{V_S} = 1 + \frac{R_F}{R_A}$$

This formula is derived for an ideal op amp. Circuits with real op amp chips may have slightly different gain values, as you will see in the lab.

Note that if you connect the inverting input terminal of your op amp chip directly to the ground, the gain of your circuit will be very large ($R_A = 0$ in the formula above) thus the output signals will be grossly distorted.

How to Build an Inverting Amplifier

You can easily convert the noninverting amplifier circuit discussed in Figure 4-6 into the basic inverting amplifier circuit shown in Figure 4-7.

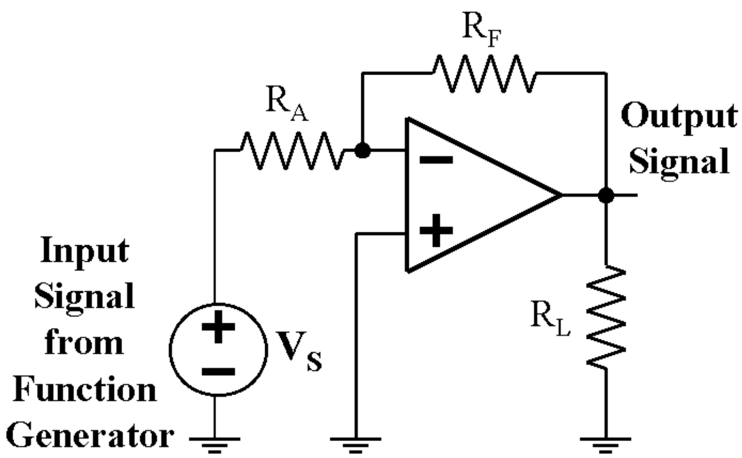


Figure 4-7**.** Basic inverting amplifier.

Compare the circuit diagrams in Figures 4-6 and 4-7.

Warning: Do not rebuild the entire circuit of Figure 4-6 in order to obtain the circuit of Figure 4-7: note that the connections between the op amp chip and each of the three resistors remain the same in both circuits. Keep these connections.
Warning: Note that connections to the power supply bus lines $+V_{CC}$ and $-V_{CC}$ are not shown in Figure 4-7 for simplicity but they are of course necessary. Many circuit diagrams with op amps do not show connections to the power supply.

To build an inverting amplifier, connect the input signal from your function generator to the inverting input terminal of the op amp through the input resistor R_A, and connect the ground bus line directly to the noninverting input of the op amp chip.

Warning: Do not connect the inverting input of your op amp directly to the function generator: your amplifier circuit must have the resistor R_A (see the note below).

The gain is derived from the node voltage equation and GRs:

$V_+ = 0$ due to connection

$V_- = V_+$ due to the GR

$$\frac{V_- - V_S}{R_A} + \frac{V_- - V_{output}}{R_F} + i_- = 0; \text{ neglect } i_- \text{ due to GR}$$

$$\text{Thus, Gain} = \frac{V_{output}}{V_S} = -\frac{R_F}{R_A}$$

This formula for the gain is derived for an ideal op amp. Circuits with real op amp chips might have slightly different gain values, as you will see in the lab.

Note that students who skip the input resistor R_A and connect the signal from the function generator directly to the inverting input of the op amp chip make a blunder: this connection results in $R_A = 0$, which leads to an infinitely large gain (see the formula above) and produces a grossly distorted, badly clipped output signal.

Potentiometers

An amplifier circuit with fixed resistors R_A and R_F has fixed gain determined by the ratio $\frac{R_F}{R_A}$. In many applications you need variable gain, for example, to control the volume of sound at the output of your audio amplifier. To make the gain variable, we use potentiometers, about which you already learned in Lab 3.

A potentiometer is simply a resistor with three terminals labeled A, B, and C, as shown on the two circuit diagrams below. The movable terminal C is called a wiper or a tap.

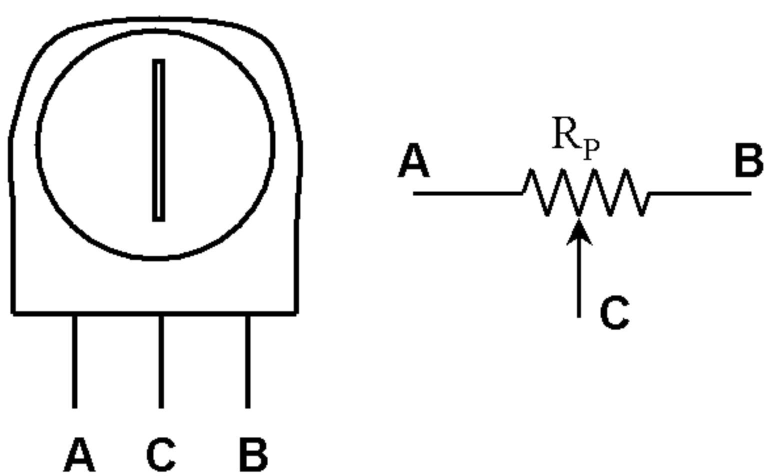


Figure 4-8. Potentiometer: (Left) Sketch of a trimming potentiometer (which you can use in this lab) with three pins corresponding to the three terminals that plug into the protoboard and a slot for a screwdriver to move the tap; (Right) circuit diagram with the same notations for the terminals.

Figure 4-8 shows a sketch of a small trimming potentiometer (trimpot in EE jargon) along with the circuit diagram. The resistance R_{AB} between the end terminals A and B of a potentiometer is fixed and equal to R_P. The resistance R_{AC} between the end terminal A and the tap C varies from zero to R_P according to the position of the tap; at the same time the resistance R_{CB} between the tap C and the other end terminal B varies from R_P to zero so that $R_{AC} + R_{CB} = R_{AB}$ at any position of the tap.

For example, for a 1-kΩ potentiometer, $R_P = 1$ kΩ, R_{AC} varies from zero to 1 kΩ, while R_{CB} varies from 1 kΩ to zero so that $R_{AC} + R_{CB} =1$ kΩ at any position of the tap.

A potentiometer is equivalent to a pair of resistors shown in Figure 4-9: the resistance between A and B is fixed and equal to R_P, while the resistance $R_X = R_{AC}$ between A and C varies from zero to R_P as the tap moves from A toward B, and at the same time the resistance $(R_P – R_X) = R_{CB}$ varies from R_P to zero.

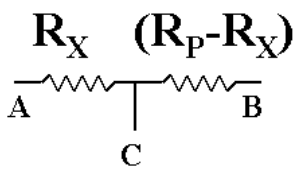


Figure 4-9. Equivalent circuit diagram of a potentiometer (compare to Figure 4-8).

In circuits, potentiometers can serve as variable voltage dividers (if all three terminals A, B, and C are connected to the circuit) or as variable resistors R_X (if terminal B is left open).

A Noninverting Amplifier Circuit with Variable Gain

Figure 4-10 shows a noninverting amplifier with a voltage divider in the input signal circuit.

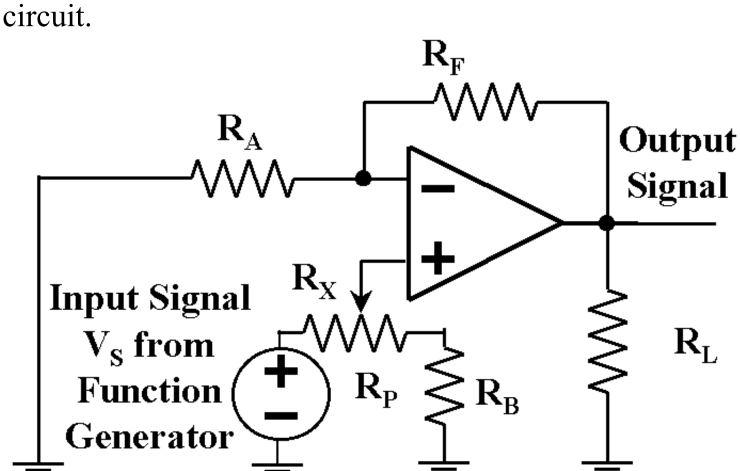


Figure 4-10. Circuit diagram of a noninverting amplifier with variable gain.

In Figure 4-10, R_X denotes the variable resistance between the potentiometer's tap and the source V_S (your function generator, which provides the input signal). R_X varies from zero to R_P. Notice that a fixed resistor R_B is added in series with the potentiometer to ensure that the gain does not get too small.

The gain of this amplifier circuit is also easy to derive from the node voltage equations and the GRs for an ideal op amp.

For the sake of clarity we can redraw the circuit diagram, replacing one potentiometer with two resistors.

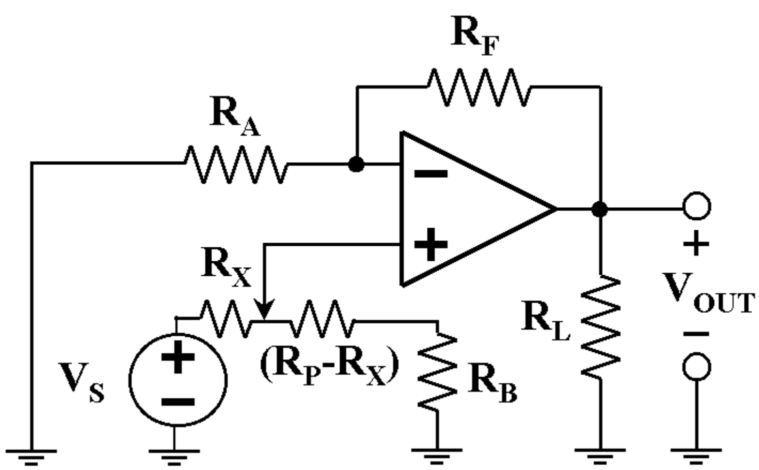


Figure 4-11. Equivalent circuit diagram of a noninverting amplifier with variable gain (compare with Figure 4-10).

Here is the result:

$$\text{Gain} = \frac{V_{OUT}}{V_S} = \left(1 + \frac{R_F}{R_A}\right) \cdot \left(\frac{R_B + R_P - R_X}{R_B + R_P}\right)$$

Note that the output signal is the product of the fixed gain of the non-inverting amplifier, which has the signal V_+ at the non-inverting input terminal (V_+ is determined by voltage division of the input signal V_S from the function generator).

An Inverting Amplifier Circuit with Variable Gain

Figure 4-12 shows the circuit diagram of a variable-gain inverting amplifier with a variable feedback resistor R_F.

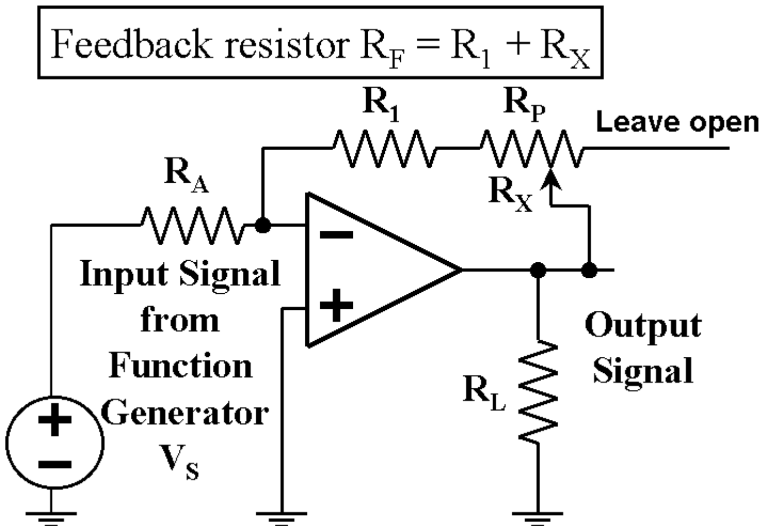


Figure 4-12. Variable-gain inverting amplifier with a variable feedback resistor R_F.

Its gain equals: $\text{Gain} = \dfrac{V_{OUT}}{V_S} = -\dfrac{R_1 + R_X}{R_A}$

Note that the gain of both variable-gain amplifiers discussed above is directly proportional to the variable resistance R_X.

Saturation of Output Signals in Amplifier Circuits: Voltage Clipping

The amplifier's output voltage cannot exceed the power supply's voltages. Since

$$V_{OUT} = V_{IN} \cdot \text{Gain}$$

the output signals can get too large if the input signals and/or the gain get too large. This is called voltage clipping, which leads to distorted signals, or bad sound in audio systems.

Three parts of Figure 4-13 show the output waveform of an amplifier in three cases related to voltage clipping. Assume that the output signal of this amplifier is fed into a speaker, which you use to listen to your favorite music.

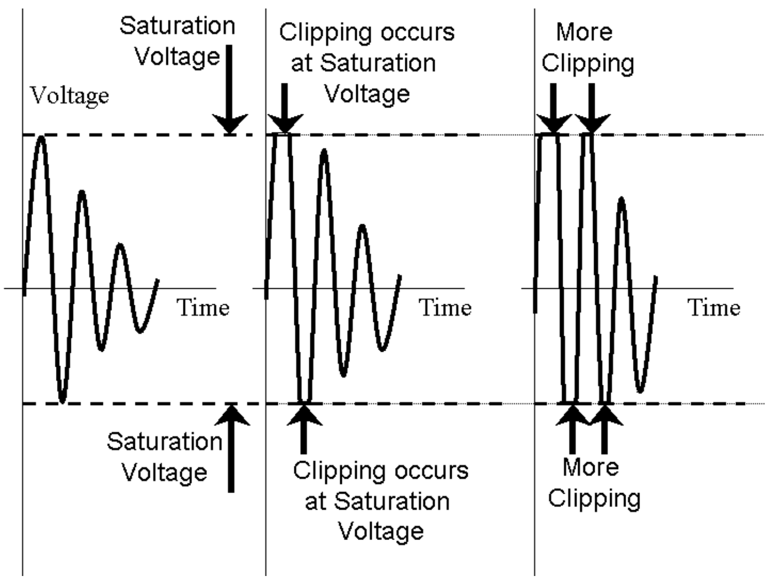


Figure 4-13. Saturation of output signals in an amplifier circuit.

On the left panel of Figure 4-13, the output signal amplitude approaches the saturation voltage but does not exceed it thus the output signal is not clipped and the sound is not distorted.

On the central panel, the output signal is clipped at the saturation voltage, distorting the sound.

On the right panel, the clipping is more significant, and the sound gets ugly.

The saturation voltage never exceeds the voltage applied from the power supply. For example, if $V_{CC} = +12$ V, the saturation voltage V_{SAT}^{+} may equal 10 V or 12 V (depending on the op amp chip), but it cannot be larger than 12 V.

The saturation also occurs at negative voltages. For example, if $-V_{CC} = -12$ V, the saturation voltage V_{SAT}^{-} may equal –12 V or –10 V (depending on the op amp chip), but it cannot exceed –12 V.

The assumption $V_{SAT}^{-} = -V_{SAT}^{+}$ is approximate: for example, in a real circuit the signals can be clipped at +10.5 V and at –10.2 V.

This is illustrated in Figure 4-14.

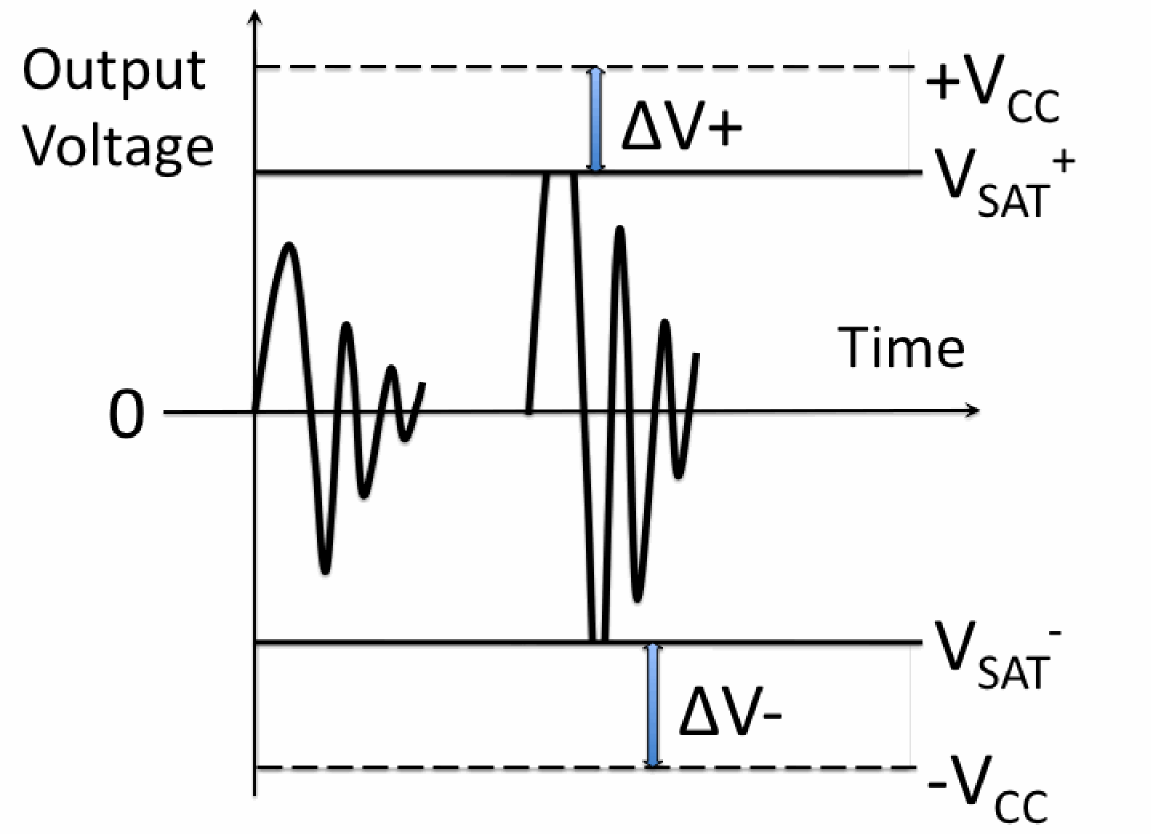


Figure 4-14. The sketch shows two output waveforms: the left one is well within the saturation limits V_{SAT}^{-} and V_{SAT}^{+} therefore it is not clipped; the right one is clipped because its voltages exceed the saturation limits. The magnitudes of saturation voltages V_{SAT}^{-} and V_{SAT}^{+} are smaller than the magnitudes of supply voltages $-V_{CC}$ and $+V_{CC}$. In real op amp chips, the margins $\Delta V- = \left|(-V_{CC}) - V_{SAT}^{-}\right|$ and $\Delta V+ = \left|(+V_{CC}) - V_{SAT}^{+}\right|$ may be slightly different.

The Bandwidth of an Amplifier

An amplifier that works well at some frequencies may fail at other frequencies. For example, an audio system built for humans may be ineffective for dolphins that use ultrasound (much higher frequencies) in their communications. Every amplifier has its bandwidth (BW), or the range of frequencies, outside which its performance deteriorates.

To determine the bandwidth of your amplifier, take 3 steps.

Step 1

Measure the gain of your amplifier over a broad range of frequencies.

Since humans hear sounds from 20 Hz to 20 kHz, audio amplifiers should be characterized at least over this hearing range.

How should we measure the gain?

Recall the familiar formula:

$$\text{Gain} = \frac{\text{Output Voltage (peak-to-peak)}}{\text{Input Voltage (peak-to-peak)}}$$

Thus, in order to determine the gain, you have to measure both amplitudes—of the input and output signals.

Since the gain may greatly vary over a broad frequency range, it is preferable to express it on the logarithmic scale using decibels:

$$\text{Gain in dB} = 20 \cdot \log_{10}\left(\frac{\text{Output Voltage (peak-to-peak)}}{\text{Input Voltage (peak-to-peak)}}\right)$$

Strictly speaking, calculations of dB require RMS voltages:

$$V_{\text{RMS}} = \frac{V_0}{\sqrt{2}} = \frac{V_{\text{peak}}}{\sqrt{2}} = \frac{V_{\text{peak-to-peak}}}{2 \cdot \sqrt{2}}$$

but the $2 \cdot \sqrt{2}$ factors in the numerator and denominator will cancel when you calculate the gain. Beware of a typical blunder: if a student uses peak-to-peak value for the input signal and RMS for the output, the gain will be wrong by about 9 dB.

At what frequencies should you measure the gain?

If you choose 20 Hz as your first frequency point, what should be your next point? Going on a linear scale to 40 Hz, 60 Hz, 80 Hz, etc., will take you forever—the lab period will end well before you reach 20 kHz. Moreover, you do not need all those points.

When data should be taken over a broad range, we use logarithmic scales.

We think in terms of decades: By definition, a decade is any interval of frequencies
(f_1, f_2)
such that
$f_2 = 10 \cdot f_1$.
For example, from 1 Hz to 10 Hz, there is one decade, and from 47 kHz to 470 kHz there is one decade as well.

In other words, over one decade the frequency increases by a factor of 10. Thus the human hearing range from 20 Hz to 20 kHz spans 3 decades. Of course, taking only one point per decade (for example, at 20 Hz, 200 Hz, 2 kHz and 20 kHz) will not be enough. Traditionally, if you take data by hand, get 3 points per decade in 1-2-5 steps such as:

10 Hz
20 Hz
50 Hz

100 Hz
200 Hz
500 Hz
etc.

Thus, in 1-2-5 steps, 10 data points cover the entire audio range from 20 Hz to 20 kHz. Figure 4-15 shows an example of gain as function of frequency measured with 3 points per decade in 1-2-5 steps.

In the lab you will use NI ELVIS Bode Analyzer, which is very convenient and fast. For automatic measurements of the gain vs. frequency, you will have to specify the start frequency, the end frequency, and the number of data points per decade (the VI will space them evenly on the logarithmic scale); usually 10 points per decade is enough.

Figure 4-16 shows an example of gain as function of frequency measured automatically with NI ELVIS Bode Analyzer. Note the parameter settings chosen for this measurements and use similar settings for your lab experiments.

Step 2

Determine the "mid-band gain" of your amplifier.

Usually, the gain of an amplifier remains at its highest and nearly constant over a certain range of frequencies: this is called the "mid-band' gain. Its numerical value is found from averaging, which you may do "by eye" in this lab. You can use either a table of gain versus frequency or a plot of data on the computer screen or a printout.

Step 3

Determine the cutoff frequencies f_1 (below the mid-band) and f_2 (above the mid-band). The bandwidth is their difference: Bandwidth = BW = $f_2 - f_1$

Away from the mid-band, the gain drops. Traditionally, the cutoff frequency is defined as the half-power frequency, where the power of the output signal equals 50% of the output power at maximal gain, provided that the input signal remains constant. In practice, the cutoff frequency is determined as a "–3 dB" frequency, at which the gain is 3 dB lower than the mid-band value.

Why –3 dB? With good accuracy, this value corresponds to 50% of the output power (assuming 100% power in the mid-band range). You will learn more details when you study filters in Lab P7.

Let us consider a numerical example.

Example: How to Find the Bandwidth from Lab Data

Step 1 (Example)

Suppose that a student obtained the following data in the lab:

Frequency, Hz	Input signal amplitude, Vppk	Output signal amplitude, Vppk
20	0.3	3.5
50	0.4	6.3
100	0.5	10.2
200	0.6	15.5
500	0.7	20.8
1 k	0.7	27.9
2 k	0.6	23.7
5 k	0.6	24.1
10 k	0.5	16.4
20 k	0.4	11.0

Figure 4-15 shows this set of data plotted with MATLAB software; the code is given below.

```
f = [20 50 100 200 500 1e3 2e3 5e3 10e3 20e3]; % frequency, Hz
Vin = [0.3 0.4 0.5 0.6 0.7 0.7 0.6 0.6 0.5 0.4]; % input, Vppk
Vout = [3.5 6.3 10.2 15.5 20.8 27.9 23.7 24.1 16.4 11.0]; % output, Vppk
semilogx(f, 20*log10(Vout./Vin), 'sk-'); grid;
xlabel('Frequency, Hz'); ylabel('Gain, dB');
title('Amplifier gain vs. frequency');
```

Note that calculations of the gain and of its decibel value are delegated to MATLAB software.

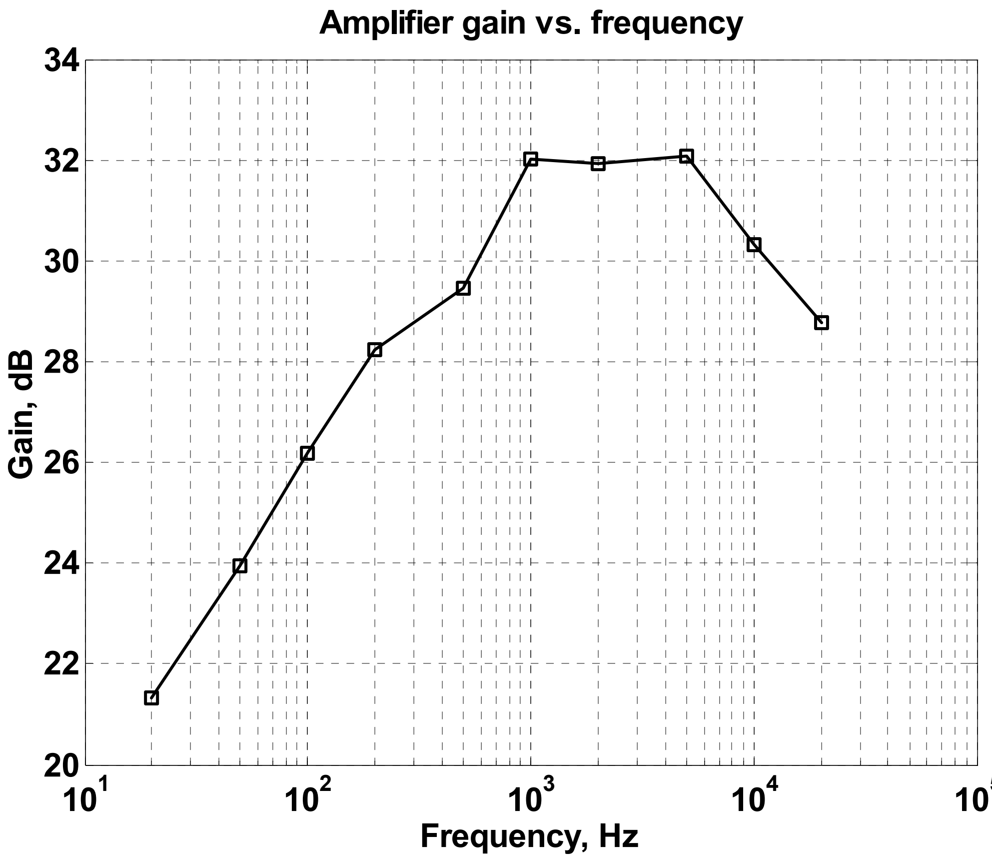


Figure 4-15. An example of gain as function of frequency. The data points are taken from the table above.

Step 2 (Example)

Determine the "mid-band gain" from the plot shown in Figure 4-15. Evidently, the mid-band gain equals 32 dB, determined over 3 data points at 1, 2, and 5 kHz where the gain is nearly constant.

Step 3 (Example)

Determine the cutoff frequencies f_1 (below the mid-band) and f_2 (above the mid-band). The bandwidth is their difference: Bandwidth = BW = $f_2 - f_1$

Determine the cutoff frequencies as "–3 dB" frequencies.
Begin with finding the "–3 dB" gain value:

$$\text{(Mid-band gain)} - 3\text{ dB} = 32\text{ dB} - 3\text{ dB} = 29\text{ dB}$$

From the MATLAB plot, find the cutoff frequencies. On the MATLAB plot, we see that the gain equals 29 dB at about 300 Hz and at about 20 kHz. Thus f_1 = 300 Hz, and f_2 = 20 kHz. The bandwidth is: BW = $f_2 - f_1$ = 19.7 kHz.

The amplifier's bandwidth in this example is relatively broad (compare to telephone communication that uses audio frequencies between 300 and 3400 Hz). However, as the only output amplifier of an audio system, it is not satisfactory, because all low-frequency sounds—all bass tones below 300 Hz—will be lost. In high-quality audio systems the amplifier should have cutoff frequencies f_1 not higher than 20 Hz, and f_2 not lower than 20 kHz so that sounds in the entire hearing range are amplified equally well.

Gain*Bandwidth Product

Since the gain of your amplifier circuit is determined by the resistors R_A and R_F rather than by the op amp chip itself, you can build amplifier circuits with various gain values

$$\text{Gain} = \frac{\text{Output Voltage (peak-to-peak)}}{\text{Input Voltage (peak-to-peak)}}$$

According to simple theory, the product of the gain and the bandwidth (more precisely, the high cutoff frequency f_2) remains constant; in other words, as you increase the gain, the bandwidth of your amplifier decreases. The manufacturers' specifications list either the G*BW product or simply the bandwidth (then they assume gain = 1). For example, if the specs lists BW = 1 MHz, and gain of your amplifier circuit equals 20, then you should read the specs as G*BW = 1 MHz and calculate the expected BW of your circuit as (1 MHz)/20 = 50 kHz (more precisely, the high cutoff frequency f_2 = 50 kHz).

In this lab, you will verify this relationship for both LM 741 and LF 356 op amp chips. Bandwidth is one of the parameters that make these chips distinct.

Figure 4-16 shows an example of lab data obtained with NI ELVIS Bode Analyzer. Note that the mid-band gain equals 36 dB (the cursor set at 10 Hz reads it as 36.11 dB) thus you have to find the high cutoff frequency f_2 where the gain drops to 33 dB, which is approximately in the middle between 10,000 Hz and 20,000 Hz (note the logarithmic axis for frequency). The cursor allows you to read out the data only at the points where they were taken (not between the points) thus, if you need better accuracy, repeat the measurement over a narrower range of frequencies but with more steps per decade.

Warning: In measurements with NI ELVIS Bode Analyzer, the input signal from the function generator should be connected to Channel 1 and the output signal from the oscilloscope should be connected to Channel 0.

Figure 4-16. An example of gain as function of frequency measured with NI ELVIS Bode Analyzer (top plot). The bottom plot shows the phase shift between the input and the output sinusoidal signals.

Phase Shifts Between Input and Output Signals in Amplifier Circuits

In our discussion of the inverting and noninverting amplifiers above, we draw a strict borderline between them based on the phase relationships between the input and the output voltages. Specifically, we assumed zero phase shift between the input and output of a noninverting amplifier and an exactly 180° phase shift between the input and output of an inverting amplifier.

Figure 4-16 shows the data taken with a noninverting amplifier and demonstrates that zero phase shift is indeed observed but only at very low frequencies. As the signal frequency increases, the shift becomes significant, and at ~200 kHz it reaches nearly 180°; in other words, at high frequencies the signals look as if the amplifier were inverting. The take-home message is that distinctions outlined above are only guidelines, not strict laws, and phase shifts should be measured.

Note that the negative sign of phase shift corresponds to the output signal delayed relative to the input. For example, the equations below describe the input and output sinusoidal voltages with period T, and the output is shifted by $-\frac{\pi}{4}$ with respect to the input.

$$v_{IN}(t) = V_{IN,\,MAX} \cdot \sin\left(\frac{2\pi}{T} \cdot t\right)$$

$$v_{OUT}(t) = V_{OUT,\,MAX} \cdot \sin\left(\frac{2\pi}{T} \cdot t - \frac{\pi}{4}\right)$$

From these equations, the input voltage reaches its first maximum at $t > 0$ when

$$\left(\frac{2\pi}{T} \cdot t\right) = \frac{\pi}{2} \text{ or } t = \frac{T}{4}$$

The output voltage reaches its first maximum at $t > 0$ when

$$\left(\frac{2\pi}{T} \cdot t - \frac{\pi}{4}\right) = \frac{\pi}{2} \text{ or } t = \frac{3T}{8} > \frac{T}{4}$$

In other words, the output signal reaches its maximum at a later time, or is indeed delayed with respect to the input.

Figure 4-16 shows an example of lab data where the output sinusoidal voltage is delayed with respect to the input. The data were taken with NI ELVIS oscilloscope, which does not read the phase shift in angles but allows measuring the delay between waveforms in microseconds by using cursors.

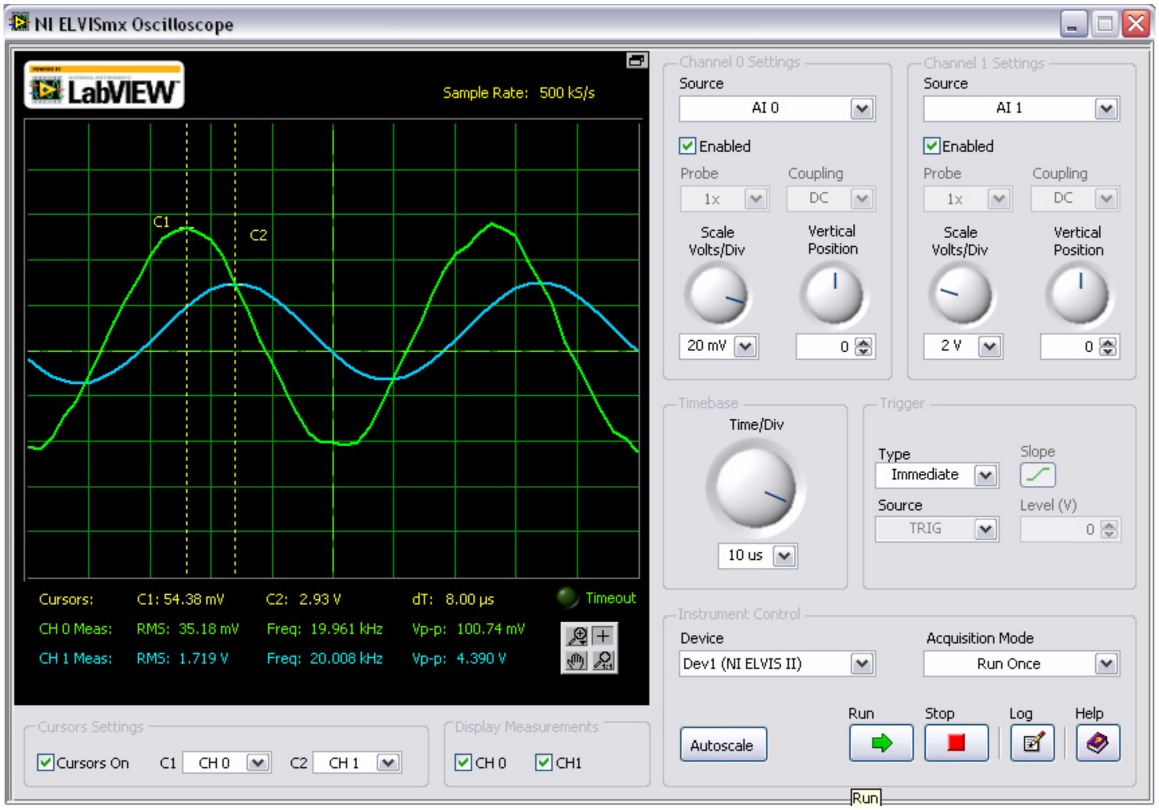


Figure 4-16. An example of lab data: the output sinusoidal voltage (blue trace) is delayed with respect to the input (green trace).

Let us consider the data in Figure 4-16 in more detail.

First of all, the peak-to-peak amplitude of the green waveform is about 100 mV and that of the blue waveform is 4.39 V, which confirms that the blue waveform shows the amplified output signal.

Secondly, the time setting of 10 µs/Div and 5 divisions between the maxima (or minima) of each waveform correspond to the period of 50 µs or the frequency equal to 20 kHz.

Thirdly, the time delay measured with two cursors is displayed as 8 µs, which equals 0.16 of the period and corresponds to $0.16 \cdot 2\pi = 1.00\,\text{rad}$, or $0.16 \cdot 360° = 57.6°$.

Buffer, or Voltage Follower Circuit

In the circuit shown in Figure 4-17, the op amp's output is connected to the inverting (–) input with a wire.

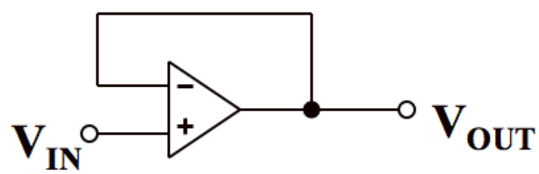


Figure 4-17. Voltage follower, or buffer circuit. Note that the connections to the power supplies +Vcc and –Vcc are not shown, although they are necessary.

Thus, by the second GR, $V_{OUT} = V_{IN}$. Note that the current into the op amp's noninverting (+) input terminal is negligible, according to the first GR.

This circuit is called voltage follower, because its output voltage follows the input.

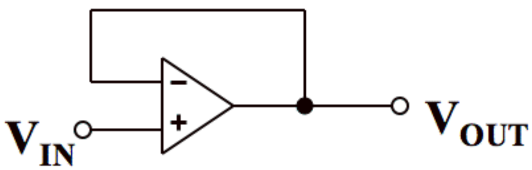
This circuit is also called buffer, because it separates the voltages and currents in parts of the circuit connected to the op amp input (upstream) from the voltages and currents in parts of the circuit connected to the op amp output (downstream), which is extremely useful in many applications.

You will see one of its applications in Pre-Lab Problem 1.

Pre-Lab

Problem 1, Part 1

The op amp shown on this diagram (see Introduction page 25) has its output is connected to the inverting (–) input with a wire.



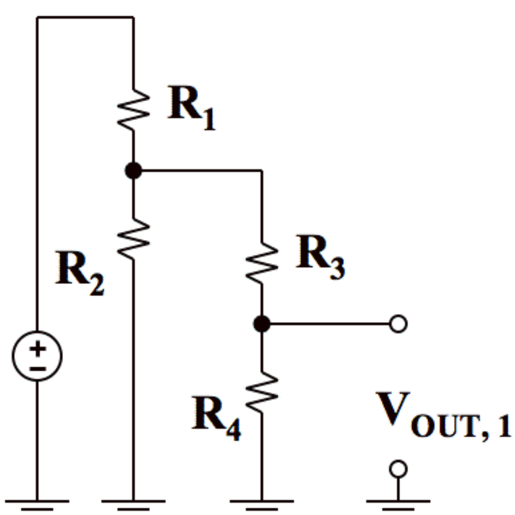
Thus, by the second GR, $V_{OUT} = V_{IN}$.

Note that the current into the op amp's non-inverting (+) input terminal is negligible, according to the first GR.

This circuit is called voltage follower, because its output voltage follows the input.

The purpose of this problem is to help you appreciate the importance of the voltage follower in a simple application.

Suppose that a student built a voltage divider of two resistors R_1 and R_2 to obtain $V_S \cdot \frac{R_2}{R_1 + R_2}$ and then decided to further divide the output voltage by connecting a second voltage divider built of R_3 and R_4 to the output of the first divider, in the hope to obtain $V_S \cdot \left(\frac{R_2}{R_1 + R_2}\right) \cdot \left(\frac{R_4}{R_3 + R_4}\right)$. The resulting circuit is shown on the diagram below.



As you can see from the diagram above, the student will actually obtain something different because of voltage and current division involving all resistors in the circuit.

Calculate the output voltage in the circuit above.

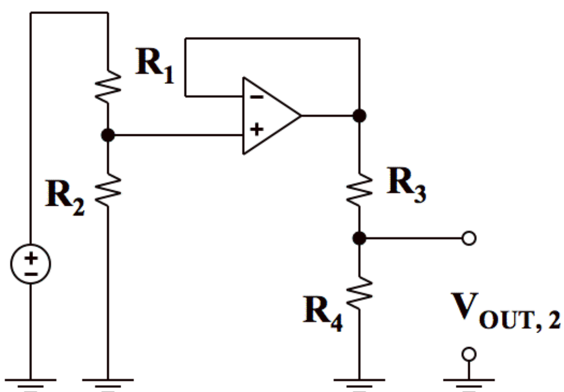
Write your answer in the algebraic form:

$V_{OUT,\,1} =$

Pre-Lab

Problem 1, Part 2

Another student decided to use an op amp buffer between the two voltage dividers, as shown below.



Apply the GRs and calculate the output voltage in the circuit with the buffer.

Write your answer in the algebraic form:

$V_{OUT,\,2} =$

Comment

In the circuit without a voltage follower, which is shown in Part 1 of this problem, the second voltage divider loads the first one by drawing the current from the node where resistors R_1 and R_2 are connected. This is called **loading.** The voltage follower, which is connected to the same node in the circuit of Part 2, does not draw any current from it. In other words, the voltage follower eliminates loading. In Part 3 of this problem, you will calculate the effect of loading on the output voltage of the circuit.

Pre-Lab

Problem 1, Part 3

Assume the source voltage $V_S = +5$ V,

$R_1 = 100\ k\Omega$, $R_2 = 200\ k\Omega$,

$R_3 = 100\ \Omega$, $R_4 = 200\ \Omega$,

and calculate $V_{OUT,\,1}$ and $V_{OUT,\,2}$ in volts, with 4 significant digits.

Problem 2, Part 1

For the variable gain, non-inverting amplifier shown in Figures 4-10 and 4-11, calculate in algebraic form the minimal and maximal gain: $\text{Gain} = \frac{V_{OUT}}{V_{IN}}$.

Problem 2, Part 2

Assume that the input resistance $R_A = 1\ k\Omega$, $R_B = R_X = 2\ k\Omega$, $R_P = 10\ k\Omega$ and the gain equals 50.
Calculate the feedback resistance R_F in $k\Omega$.

Problem 2, Part 3

For the variable gain, inverting amplifier shown in Figure 4-12, calculate in algebraic form the minimal and maximal magnitude of gain: $|\text{Gain}| = \left|\frac{V_{OUT}}{V_{IN}}\right|$.

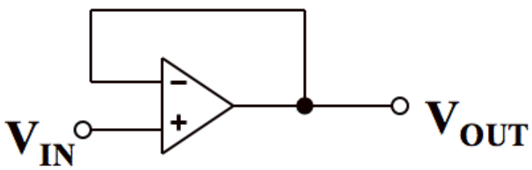
Problem 2, Part 4

Assume that the input resistance $R_A = 1\ k\Omega$ and the gain equals 50.
Calculate the feedback resistance R_F in $k\Omega$.

Pre-Lab

Problem 1, Part 1

The op amp shown on this diagram (see Introduction page 25) has its output is connected to the inverting (–) input with a wire.



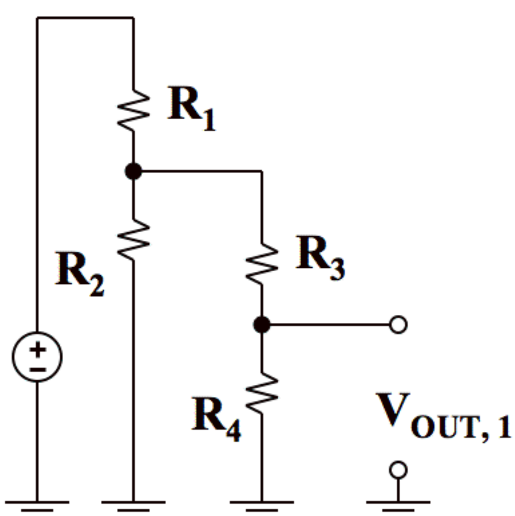
Thus, by the second GR, $V_{OUT} = V_{IN}$.

Note that the current into the op amp's non-inverting (+) input terminal is negligible, according to the first GR.

This circuit is called voltage follower, because its output voltage follows the input.

The purpose of this problem is to help you appreciate the importance of the voltage follower in a simple application.

Suppose that a student built a voltage divider of two resistors R_1 and R_2 to obtain $V_S \cdot \frac{R_2}{R_1 + R_2}$ and then decided to further divide the output voltage by connecting a second voltage divider built of R_3 and R_4 to the output of the first divider, in the hope to obtain $V_S \cdot \left(\frac{R_2}{R_1 + R_2} \right) \cdot \left(\frac{R_4}{R_3 + R_4} \right)$. The resulting circuit is shown on the diagram below.



As you can see from the diagram above, the student will actually obtain something different because of voltage and current division involving all resistors in the circuit.

Calculate the output voltage in the circuit above.

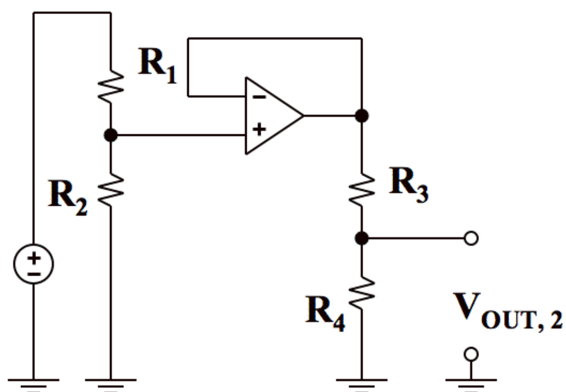
Write your answer in the algebraic form:

$V_{OUT,\,1}$ =

Pre-Lab

Problem 1, Part 2

Another student decided to use an op amp buffer between the two voltage dividers, as shown below.



Apply the GRs and calculate the output voltage in the circuit with the buffer.

Write your answer in the algebraic form:

$V_{OUT,\,2}$ =

Comment

In the circuit without a voltage follower, which is shown in Part 1 of this problem, the second voltage divider loads the first one by drawing the current from the node where resistors R_1 and R_2 are connected. This is called **loading.** The voltage follower, which is connected to the same node in the circuit of Part 2, does not draw any current from it. In other words, the voltage follower eliminates loading. In Part 3 of this problem, you will calculate the effect of loading on the output voltage of the circuit.

Pre-Lab

Problem 1, Part 3

Assume the source voltage V_S = +5 V,

R_1 = 100 kΩ, R_2 = 200 kΩ,

R_3 = 100 Ω, R_4 = 200 Ω,

and calculate $V_{OUT,\,1}$ and $V_{OUT,\,2}$ in volts, with 4 significant digits.

Problem 2, Part 1

For the variable gain, non-inverting amplifier shown in Figures 4-10 and 4-11, calculate in algebraic form the minimal and maximal gain: $\text{Gain} = \dfrac{V_{OUT}}{V_{IN}}$.

Problem 2, Part 2

Assume that the input resistance R_A = 1 kΩ, R_B = R_X = 2 kΩ, R_P = 10 kΩ and the gain equals 50.
Calculate the feedback resistance R_F in kΩ.

Problem 2, Part 3

For the variable gain, inverting amplifier shown in Figure 4-12, calculate in algebraic form the minimal and maximal magnitude of gain: $\left|\text{Gain}\right| = \left|\dfrac{V_{OUT}}{V_{IN}}\right|$.

Problem 2, Part 4

Assume that the input resistance R_A = 1 kΩ and the gain equals 50.
Calculate the feedback resistance R_F in kΩ.

Pre-Lab

Problem 3, Part 1

Use the manufacturer's specs for the G*BW product of LM 741, calculate the value of high cutoff frequency in Hz in the noninverting amplifier circuit (Figures 4-10 and 4-11) for several gain values in increments of a factor of 2.

Organize your results in the table form:

Gain	f_{cutoff} (Hz)
2	
4	
8	
16	
32	
64	

Problem 3, Part 2

Repeat for LF 356.
Organize your results in the table form:

Gain	f_{cutoff} (Hz)
2	
4	
8	
16	
32	
64	

Briefly discuss the difference between the two op amp chips.

Pre-Lab

Problem 4, Part 1

Use Multisim to simulate the noninverting variable-gain amplifier (Figure 4-10) with the following components: $R_A = R_B = 1\ k\Omega$, $R_P = R_F = 100\ k\Omega$, $R_L = 10\ k\Omega$, op amp LF 356H, power supply voltages –12 V and +12 V. Use the input 1 kHz sinusoidal signal 100 mVp from the function generator; monitor the input signal with Channel A of the oscilloscope and monitor the output signal with Channel B of the oscilloscope.

(a) Make sure that you observe both the input and output as sinusoidal waveforms
(b) Measure the gain at various positions of the potentiometer's tap
(c) Verify the minimal and maximal gain values.
(d) Provide a printout of the oscilloscope plot which shows the minimal gain, and another printout of the oscilloscope plot which shows the maximal gain.

Save your Multisim file.

Comment:

The purpose of this assignment is to help students prepare for in-lab work. Building circuits with op amps may be challenging to students who have not done it before. Specific blunders observed in the lab range from misunderstanding of how to connect the pins of an op amp chip to forgetting that both positive and negative supply voltages are needed for proper operation of the circuit.

Pre-lab work with Multisim may help especially if the software model is elaborated enough to mimic what happens if one of the supply voltages is not applied or if the output signal voltage gets too large.

Interestingly, the software models in Multisim database vary from overly simple (in which the output signal "exists" even if the op amp is not connected to power supplies) to more realistic (which are sensitive to whether the op amp is connected to both power supplies, and mimic voltage clipping of the output signals as well as frequency-dependent phase shifts between the input and output sinusoidal voltages).

In our experience, the model for LF 356H is more realistic than others thus we recommend using it in the pre-lab simulation even though you could use other chips in the lab.

This is the end of the required pre-lab.

The following parts (pages 31–32) are optional, for extra credit.

Pre-Lab (Optional, for extra credit)

Problem 4, Part 2

Continue the simulation of the noninverting variable-gain amplifier (Figure 4-10), which you started in Problem 4 Part 1; use the same circuit parameters.

(a) Observe clipping of the output signal when the input signal amplitude is increased and the amplifier gain is maximal; record the smallest peak amplitude of the output signal, at which the clipping is observed

(b) Vary the positive supply voltage from +12 V to +10 V and to +8 V; repeat (a); note whether the output waveform is clipped only at positive voltages or at both positive and negative voltages

(c) Use the positive power supply voltage of +12 V and vary the negative supply voltage from –12 V to –10 V and –8 V. Repeat (a); note whether the output waveform is clipped only at negative voltages or at both positive and negative voltages

(d) Refer to Figure 4-14 (page 15) and record V_{SAT}^{+}, $\Delta V+$, V_{SAT}^{-}, $\Delta V-$.

Problem 5, Part 1

Study the manufacturers' specs for LM 741, page 3, output voltage swing. Assume that Output voltage swing = $V_{SAT}^{+} - V_{SAT}^{-}$. Refer to pages 14–15 of the Introduction.
Determine ΔV; for simplicity, assume $\Delta V- = \Delta V+$.
Organize your results in the table form. List both the minimal and typical values.

Op Amp LM 741	$\Delta V = \lvert V_{CC} - V_{SAT} \rvert$	
Supply +15 V and –15 V	Load resistance = 2 kΩ	Load resistance = 10 kΩ
Minimal ΔV		
Typical ΔV		

Problem 5, Part 2

Repeat for LF 356.
Organize your results in the table form. List both the minimal and typical values.

Op Amp LF 356	$\Delta V = \lvert V_{CC} - V_{SAT} \rvert$	
Supply +15 V and –15 V	Load resistance = 2 kΩ	Load resistance = 10 kΩ
Minimal ΔV		
Typical ΔV		

Pre-Lab (Optional, for extra credit)

Problem 6, Part 1

Consider two sine waves at $f_1 = 10$ kHz

$$v_1(t) = V_{1,MAX} \cdot \sin(2\pi f_1 t)$$

$$v_2(t) = V_{2,MAX} \cdot \sin(2\pi f_1 t + \alpha_2) = V_{2,MAX} \cdot \sin\left(2\pi f_1 \cdot \left(t + \Delta t_2\right)\right)$$

shifted by $\alpha_2 = 50$ degrees. Calculate the time shift Δt_2 in μs.

Problem 6, Part 2

Repeat for two sine waves at $f_3 = 50$ kHz

$$v_3(t) = V_{3,MAX} \cdot \sin(2\pi f_3 t)$$

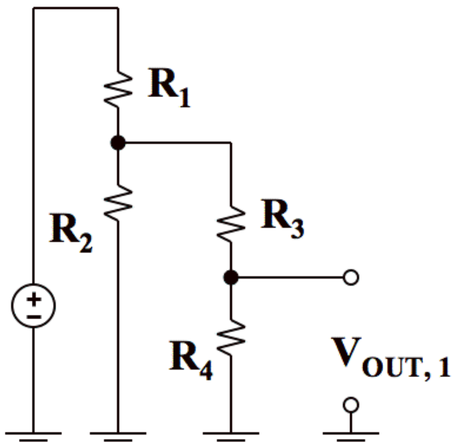
$$v_4(t) = V_{4,MAX} \cdot \sin(2\pi f_3 t + \alpha_4) = V_{2,MAX} \cdot \sin\left(2\pi f_3 \cdot \left(t + \Delta t_4\right)\right)$$

shifted by $\Delta t_4 = 0.5$ μs. Calculate the shift α_4 in degrees.

In-Lab Work

Part 1: Buffers

□ Build the following circuit:



$R_1 = 100\ k\Omega$,

$R_2 = 200\ k\Omega$,

$R_3 = 100\ \Omega$,

$R_4 = 200\ \Omega$

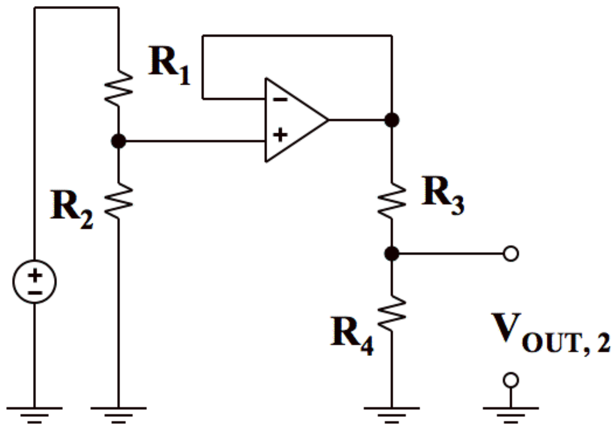
Use the +5 V DC Supply to supply Vs (terminal 54).

□ From the NI ELVISmx Instrument Launcher, launch the DMM.

□ Use the DMM to measure V_{OUT}. Record the value in the following table.

	V_{OUT} (V)
Without Buffer	
With Buffer	

□ Now add a buffer into the circuit as follows:



$R_1 = 100\ k\Omega$, $R_2 = 200\ k\Omega$, $R_3 = 100\ \Omega$, $R_4 = 200\ \Omega$.

Use LM 741.

You will also have to connect the op amp power lines (pins 4 and 7) to the VPS SUPPLY+ and SUPPLY–.

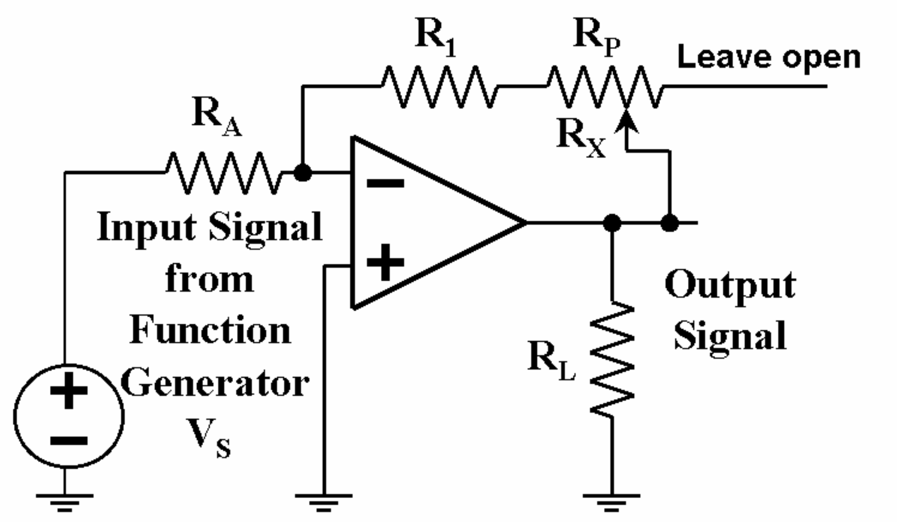
□ Launch the VPS VI and set the SUPPLY values to ± 8 V.

□ Use the DMM to measure V_{OUT} and record the value in the table.

Part 2: Inverting Amplifier

□ Turn on the NI ELVIS II.

□ Build the circuit for the following inverting amplifier circuit. Use AI channels 0 and 1 as the inputs for the OSCOPE.



$R_A = 1\ k\Omega$, $R_1 = 1\ k\Omega$, $R_P = 100\ k\Omega$ pot, $R_L = 1\ k\Omega$

Don’t forget to wire $\pm V_{CC}$ to the op amp supply voltages.

□ Power on the PB.

□ Open the NI ELVISmx Instrument Launcher and launch the VPS, FGEN, and OSCOPE VIs.

□ On the VPS set SUPPLY+ to be 8 V and SUPPLY– to be –8 V.

□ On the FGEN, create a 1 kHz, 200 mV_{PPK} sine wave with 0 V DC offset.

□ Run the VPS, FGEN, and OSCOPE VIs.

□ Adjust the settings on the OSCOPE to clearly view both signals.

□ Adjust the resistance of the potentiometer, until you have a gain of 50.

□ **Create a printout of the plot showing a gain of 50.**

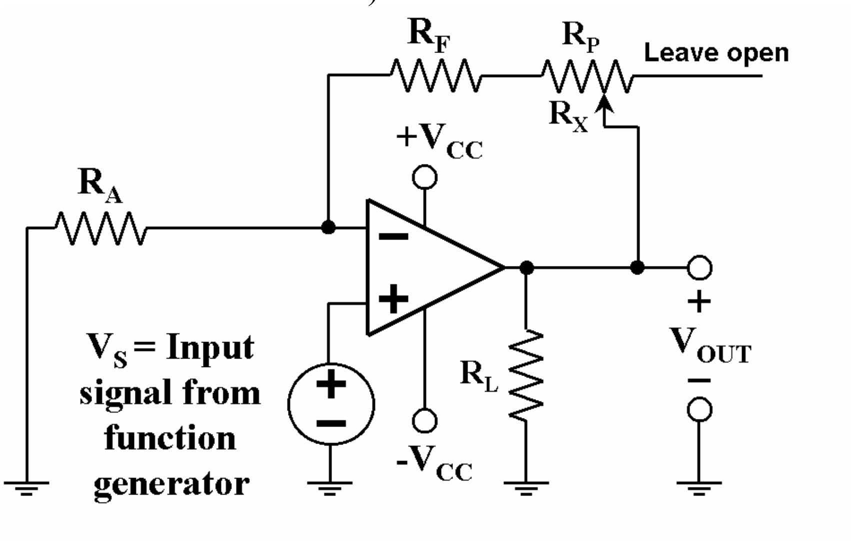
□ Record the value of R_X which yields this gain:

R_X = _________ Ω

□ Power off the PB.

Part 3: Noninverting Amplifier

□ Build the circuit for the following noninverting amplifier circuit. Use AI channels 0 and 1 as the inputs for the OSCOPE. (*Hint*: you only have to change a few wires; there is no need to start from scratch).



R_A = 1 kΩ, R_F = 1 kΩ, R_P = 100 kΩ pot, R_{LOAD} = 1kΩ

Don't forget to wire ±V_{CC} to the op amp supplies.

□ Power on the PB.

□ On the VPS, set SUPPLY+ to be 8 V and SUPPLY– to be –8V.

□ On the FGEN, create a 1 kHz, 100 mV_{PPK} sine wave with 0 V DC offset.

□ Run the VPS, FGEN, and OSCOPE VIs.

□ Adjust the settings on the OSCOPE to clearly view both signals.

□ Adjust the resistance of the potentiometer, until you have a gain of 100.

□ **Create a printout of the plot showing a gain of 100.**

□ Record the value of R_X which yields this gain:

R_X = ________ Ω

Part 4: Gain Bandwidth

□ Continue using your circuit from Part 3 for this section. However, change your circuit so that AI channel 0 is the output voltage, and AI channel 1 is the input signal (just switch the wires). This is required for the Bode plotter VI.

□ Reduce the resistance of R_X to 0 Ω (corresponds to gain = 2).

□ From the NI ELVISmx Instrument Launcher, launch the Bode plotter VI.

□ On the Bode plotter VI set the following settings:

Start Frequency = 10 Hz

Stop Frequency = 200 kHz

Steps = 10 (per decade)

Peak Amplitude = 100 mV

Op-Amp Signal Polarity = normal

Mapping = logarithmic

□ **Create a printout of the Bode plot.**

□ Record the cutoff frequency in the following table (i.e., the point where the gain is 3 dB less. If you are unable to see the cutoff point due to the hardware not providing enough range, then note it):

Gain	f_{cutoff} (Hz)
2	
4	
8	
16	
32	
64	

□ Repeat the measurement for each of the other gains. **Print out the plot each time.**

Part 5: Gain Bandwidth Again

□ Repeat Part 3, this time using the LF 356 Op Amp. It has the same pins as the 741, so all you will need to do is directly exchange them.

□ Record the cutoff frequency in the following table (i.e., the point where the gain is 3 dB less. If you are unable to see the cutoff point due to the hardware not providing enough range, then note it):

Gain	f_{cutoff} (Hz)
2	
4	
8	
16	
32	
64	

This is the end of the required lab. If you are not going to continue with the explorations, power off the PB and NI ELVIS II and clean up your workstation.

Part 6: Clipping (optional)

□ Switch your circuit to use the 741 op amp. Also make sure that the input signal is on AI channel 0 and the output signal is on AI channel 1.

□ Set $R_X = 100\ k\Omega$.

□ Change R_L to be 2 kΩ

□ Using the FGEN create a 1 kHz sine wave.

□ On the VPS set SUPPLY+ to be 8 V and SUPPLY– to be –8 V.

□ On the FGEN increase $V_{PPK,\ IN}$ until clipping of the output waveform occurs. Record the value of $V_{OUT,MAX}$ and $V_{OUT,MIN}$ in the table below.
$\Delta V+ = V_{SUPPLY+} - V_{OUT,MAX}$
$\Delta V- = V_{SUPPLY-} - V_{OUT,MIN}$

$R_L = 2\ k\Omega$

SUPPLY+ (V)	SUPPLY– (V)	$V_{OUT,MAX}$ (V)	$V_{OUT,MIN}$ (V)	ΔV+ (V)	ΔV– (V)
8	–8				
10	–10				
12	–12				

□ Repeat the measurement for each other value table entries.

□ Change R_L to be 10 kΩ

□ Repeat the measurements for the following table:

$R_L = 10\ k\Omega$

SUPPLY+ (V)	SUPPLY– (V)	$V_{OUT,MAX}$ (V)	$V_{OUT,MIN}$ (V)	ΔV+ (V)	ΔV– (V)
8	–8				
10	–10				
12	–12				

Part 7: Frequency response (optional)

□ Continue to use the circuit from Part 5.

□ Set R_X such that the circuit has a gain of 64.

□ On the VPS set SUPPLY+ = 12V and SUPPLY– = –12V.

□ On the FGEN create a 100 mV_{PPK} 2 kHz sine wave.

□ Notice how the output signal is now appears to be shifted. Use the cursors to measure how far the output has shifted (in seconds).

□ **Create a printout of the plot with the cursors on it.**

□ Repeat this measurement for a 5 kHz, 10 kHz, and 20 kHz input signals. **Create printouts of each plot (with cursors).**

Post-Lab

Problem 1

Refer to Pre-Lab Problem 1 and In-Lab Part 1 on the role of buffer in voltage divider circuits.

Calculate the percentage difference

$$\frac{Measured - Calculated}{Calculated} \cdot 100\%$$

between the ouput voltage values: (a) without the buffer, and (b) with the buffer.

Briefly discuss agreement/disagreement of experiment and theory; explain the role of the buffer.

Problem 2, Part 1

Refer to Pre-Lab Problem 2 and In-Lab Part 2 on the variable gain, inverting amplifier shown in Figure 4-12.

Calculate the percentage difference

$$\frac{Measured - Calculated}{Calculated} \cdot 100\%$$

between the values of the feedback resistance that ensures the gain magnitude

$\left|\text{Gain}\right| = \left|\frac{V_{OUT}}{V_{IN}}\right|$ equal to 50. Note that the feedback resistance is $R_X + R_F$.

Briefly discuss agreement/disagreement of experiment and theory.

Problem 2, Part 2

Repeat for the variable gain, noninverting amplifier shown in Lab Part 3.

Calculate the percentage difference

$$\frac{\text{Measured} - \text{Calculated}}{\text{Calculated}} \cdot 100\%$$

between the values of the feedback resistance that ensures the gain equal to 100. Note that the feedback resistance is $R_X + R_F$.

Briefly discuss agreement/disagreement of experiment and theory.

Post-Lab
Problem 3, Part 1
Refer to Pre-Lab Problem 3 and In-Lab Part 4 on the Gain*Bandwidth product for the noninverting amplifier circuit with LM 741.

Organize your results in the table form:

Gain	f_{cutoff} (Hz), caclulated	f_{cutoff} (Hz), measured	% difference
2			
4			
8			
16			
32			
64			

Calculate the percentage difference

$$\frac{Measured - Calculated}{Calculated} \cdot 100\%$$

between the values of the cutoff frequency at each gain value.
Briefly discuss agreement/disagreement of experiment and theory.

Post-Lab

Problem 3, Part 2
Refer to Pre-Lab Problem 3 and In-Lab Part 5 on the Gain*Bandwidth product for the noninverting amplifier circuit with LF 356.

Organize your results in the table form:

Gain	f_{cutoff} (Hz), caclulated	f_{cutoff} (Hz), measured	% difference
2			
4			
8			
16			
32			
64			
Max. gain			

Calculate the percentage difference

$$\frac{Measured - Calculated}{Calculated} \cdot 100\%$$

between the values of the cutoff frequency at each gain value.
Briefly discuss agreement/disagreement of experiment and theory.

Problem 3, Part 3
Briefly discuss the difference between the two op amp chips—LM 741 and LF 356.

This is the end of the required Pre-Lab.

The following parts are Optional, for extra credit.

Post-Lab (Optional, for extra credit)
Problem 4
Refer to Pre-Lab Problem 4 Part 2 and Problem 1, and to In-Lab Part 6. Analyze the clipping conditions in the noninverting variable-gain amplifier (Figure 4-10) based on LM 741, which you calculated in the Pre-Lab and measured in the lab.

Compare ΔV values from pre-lab and from in-lab:
Are ΔV– and ΔV+ equal each other? Briefly discuss the agreement/disagreement between the pre-lab calculations and lab data.
How do they depend on the supply voltages?
How do the measured ΔV– and ΔV+ agree/disagree with manufacturers' specs?
Does the measured dependence on R_{load} agree with the specs?

Problem 5

Refer to Pre-Lab Problem 6 and In-Lab Part 7.

From the time shifts in μs between the input and output sinusoidal waveforms that you measured at 2, 5, 10, and 20 kHz, calculate the shift in degrees for each frequency.

Compare the results of your calculations with the results of automatic measurements with NI ELVIS Bode Analyzer.

Explain which of the plots recorded with NI ELVIS Bode Analyzer should be used.

Organize your results in the table form

	Measurements of waveforms		Measurements with NI ELVIS Bode Analyzer
Frequency, kHz	Shift in μs	Shift in degrees	Shift in degrees
2			
5			
10			
20			

Briefly discuss the agreement/disagreement between the two ways of measurements.

