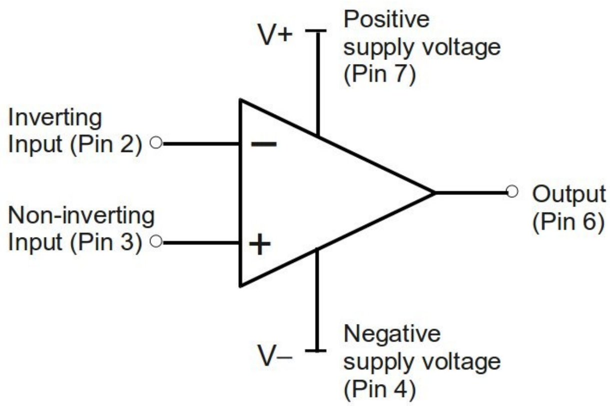
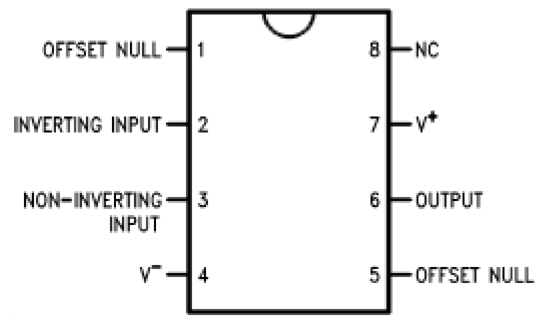
Lab 9: Operational amplifiers II (version 1.5)

WARNING: Use electrical test equipment with care! Always double-check connections before applying power. Look for short circuits, which can quickly destroy expensive equipment.

LM741 and LF411 Op-amps

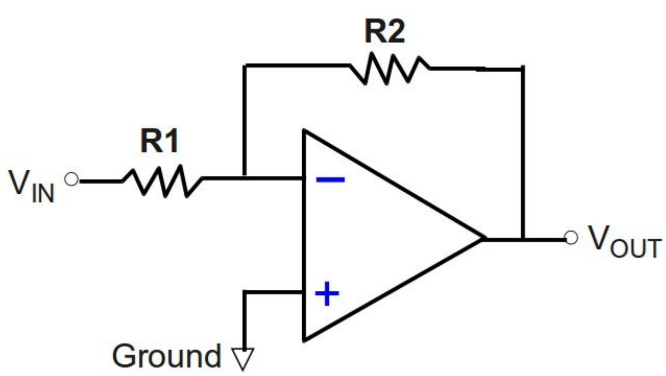
The LF411 and LM741 are general purpose operational amplifiers. The LM741 design dates back to the late 1960s and uses bipolar-junction transistors (BJTs). The LF411 (studied in Lab 8) uses junction field-effect transistors (JFETs) to achieve higher performance. Both are manufactured in the same dual inline pin (DIP) arrangement with two rows of four connectors. The package is oriented with a semi-circle notch located between pins 1 and 8. Pins 1, 5, and 8 are not used.





Gain-bandwidth product

The circuit shown below was studied in Lab 8. The gain of this amplifier is: $V_{OUT}/V_{IN} = -R2/R1$, where the minus sign indicates a 180° phase-shift.



A circuit designer must be very careful with this formula. It suggests that any amount of gain can be attained by adjusting the resistor ratio. In addition, the simple formula ignores complications introduced by operating at high frequencies.

The gain-bandwidth product of an op-amp characterizes its ability to provide the desired gain at a chosen operating frequency. This number is listed on the manufacturer's specification sheet. It is best illustrated by example. An op-amp with gain-bandwidth product of 1 MHz can provide a *maximum* gain as shown in the following table:

Frequency	**Maximum gain**
1 MHz	1 (0 dB)
100 kHz	10 (20 dB)
20 kHz	50 (34 dB)
5 kHz	200 (46 dB)

Notice that the product of Frequency x Gain = 10^6 Hz = 1 MHz. This op-amp would not be able to amplify more than 10x at 100 kHz. If the application calls for more gain, a second stage would be needed or a higher spec op-amp could be substituted.

The goal here is to use the Bode analyzer to find the gain-bandwidth product of both the LM741 and LF411. Build the above circuit following the same procedure as in Lab 8. Always measure components before placing them in the circuit as you will need accurate values for the analysis. With the Elvis board powered off, connect pin 7 to the +15V and pin 4 to –15V voltage sources on the lower left. Be sure to connect the non-inverting op-amp input to the power supply ground on the Elvis board (adjacent to the ±15V DC supply pins). Set an appropriate gain with R1 and R2 and display the amplitude response (V_{OUT}/V_{IN}) as a function of frequency using the Bode tool. You are looking for behavior resembling a low-pass filter but *without* any external capacitor present in the circuit. The gain should exhibit a sharp rolloff/reduction from the nominal value of –R2/R1 at sufficiently high frequencies.

Note: One must be careful not to generate an output signal that exceeds the $\pm$ 15V limits of the power supply. For example, if the peak amplitude of the Bode analyzer is set for 1V and R2/R1 = 100, the amplifier will clamp the gain at a much lower value (below 15) and thereby greatly distort the data. Setup your circuit so this output clipping does not occur by reducing the gain, lowering the input voltage level, or both.

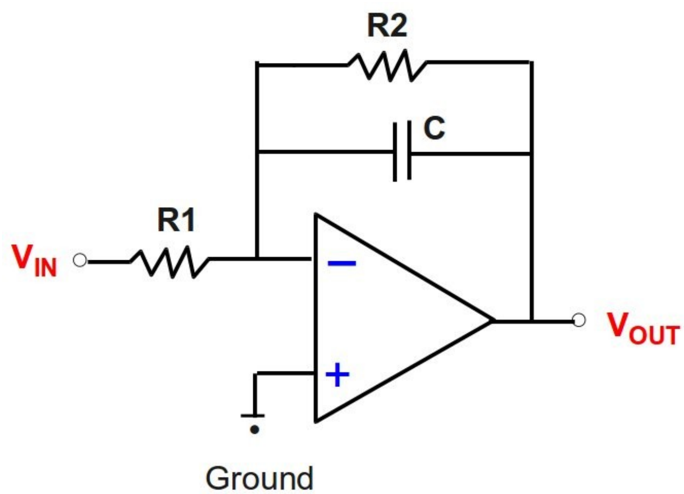
In the high frequency range (i.e. significantly above the cutoff kink), you can read the gain at several frequencies and determine the gain-bandwidth product of each op-amp. When you have values for both devices, show them to the instructor.

Slew rate

Another practical issue with op-amps is that they cannot reach an arbitrary output voltage, infinitely fast. This limitation is called slewing. Slewing of an op-amp can be observed using a fast square-wave voltage input V_{IN} (if using the external function generator, set for High-Z with no offset). Monitor the input signal on Channel 1 of the oscilloscope. If distortion of this wave occurs when the signal is connected to the op-amp, you should increase the resistor values. Use a scope probe to look at the output waveform (V_{OUT}) on the second channel. Adjust the input voltage, frequency, and gain as necessary to cause the output waveform to deviate from an ideal square wave. Be aware of potential clipping problems described in the preceding paragraph. A sketch of a slewed square wave is shown in the lecture slides. The slope of the leading edge of the output waveform defines the slew rate, expressed in Volts (on vertical scale) per μs (on horizontal scale). Measure the slew rate for both the LM741 and LF411 and show to the instructor.

Low-pass filter (integrating amplifier)

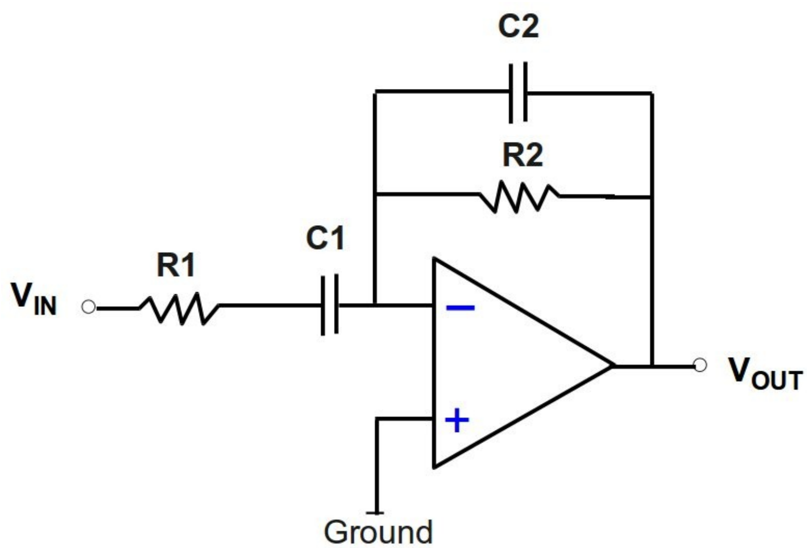
When designing an active filter circuit, one must be aware of limitations imposed by the op-amp such as its gain-bandwidth product and slew rate. Build the following circuit using the LF411 with R1 = R2 = 4.7 kΩ and C = 10 nF.



Launch the Bode analyzer and scan the frequency from 100 Hz to 20 kHz. This range corresponds to audio frequencies where the op-amp should behave ideally. If the ratio R2/R1 is increased significantly, however, this won't be the case. Confirm that you have low-pass filter behavior and save the data for later analysis.

Band-pass filter

The band-pass filter combines the characteristics of the low- and high-pass circuits. Modify the low-pass amplifier by building the following circuit with component values: R1 = 470 Ω, R2 = 4.7 kΩ , C1 = 330 nF, and C2 = 22 nF (use disc ceramic capacitors if available). Measure the values with the Elvis board DMM. Do not stray too far (> 20%) from these specified values or the circuit will not function as a band-pass filter.



Repeat the Bode analyzer measurement for the same span of frequencies. You should see distinctly different behavior in both amplitude and phase compared to the low-pass filter. In particular, the amplitude response should exhibit on obvious peak/plateau corresponding to the central passband frequencies. If this is not the case, troubleshoot the circuit using the frequency generator and oscilloscope functions of the Elvis board. When acceptable Bode data is obtained, save it to a .txt file for analysis.

Writeup

1) Analyze the data of the low-pass and band-pass amplifiers by providing model curves for both the voltage amplitude and phase. As in previous labs with passive components (only resistors, capacitors, and inductors), the response of the above active filters is a complex number (G). For the inverting amplifier it is the ratio of the feedback impedance (Z_F) to the input impedance (Z_{IN}) for an ideal op-amp:

$$G = \frac{V_{OUT}}{V_{IN}} = -\frac{Z_F}{Z_{IN}}$$

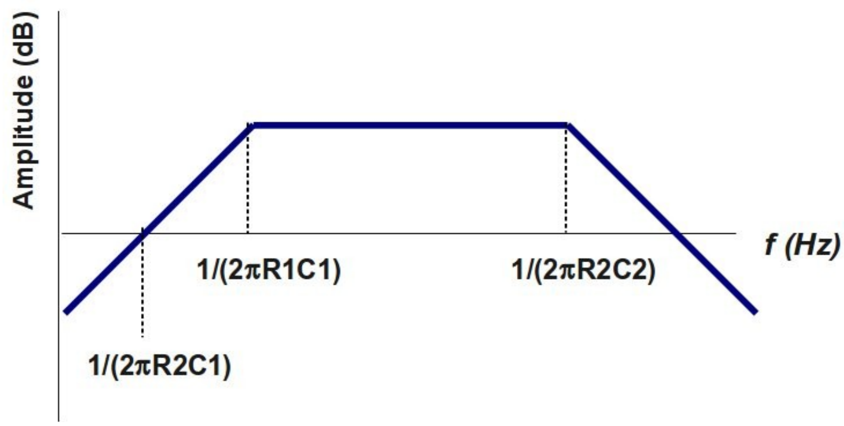
For the low-pass amplifier Z_{IN} = R1; Z_F is the parallel combination of R2 and C2. The band-pass amplifier has Z_{IN} = R1 in series with C1; Z_F = R2 in parallel with C2. The amplitude (dB) and phase (radians) are:

$$\text{Amplitude (dB)} = 20\log_{10}|G|$$

$$\text{Phase (rad)} = \text{atan}\left[\frac{\text{Im}(G)}{\text{Re}(G)}\right]$$

You will need to convert radians to degrees to match the Bode analyzer output. Make four plots (2 for each circuit) showing amplitude (dB) and phase (degrees) as a function of frequency (on a log-10 scale) to compare with your data. Provide your formulas for G for both circuits. It is recommended a program like MatLab, Scilab, Octave, or LabView be used to handle the complex algebra of G automatically.

2) Use your band-pass filter model from part 1) to design (do not build) a circuit with a passband frequency range of approximately 10--100 kHz. The amount of gain (amplitude) is not important, provided it is maximum in the passband. The approximate break points (corner frequencies) of the band-pass amplifier can be estimated using the following Bode plot. The break point frequencies are give by the various RC combinations:



where the slopes are ±20 dB/decade and the frequency axis is on a log10 scale. Determine values of R1, R2, C1, and C2 to set these frequency points at approximately 1 kHz, 10 kHz, and 100 kHz. The amplitude of the curve is not important; the goal is to obtain the desired frequency response. Calculate and display the amplitude and phase Bode plots of your design.

Send parts 1) and 2) as a single .pdf file to the instructor before the next class meeting.