

The Operational Amplifier:

Inverting and Non-inverting Gain Configurations

Gain-Bandwidth Product Relationship

Frequency Response Limitation

Transfer Function Measurement

DC Errors

Objective

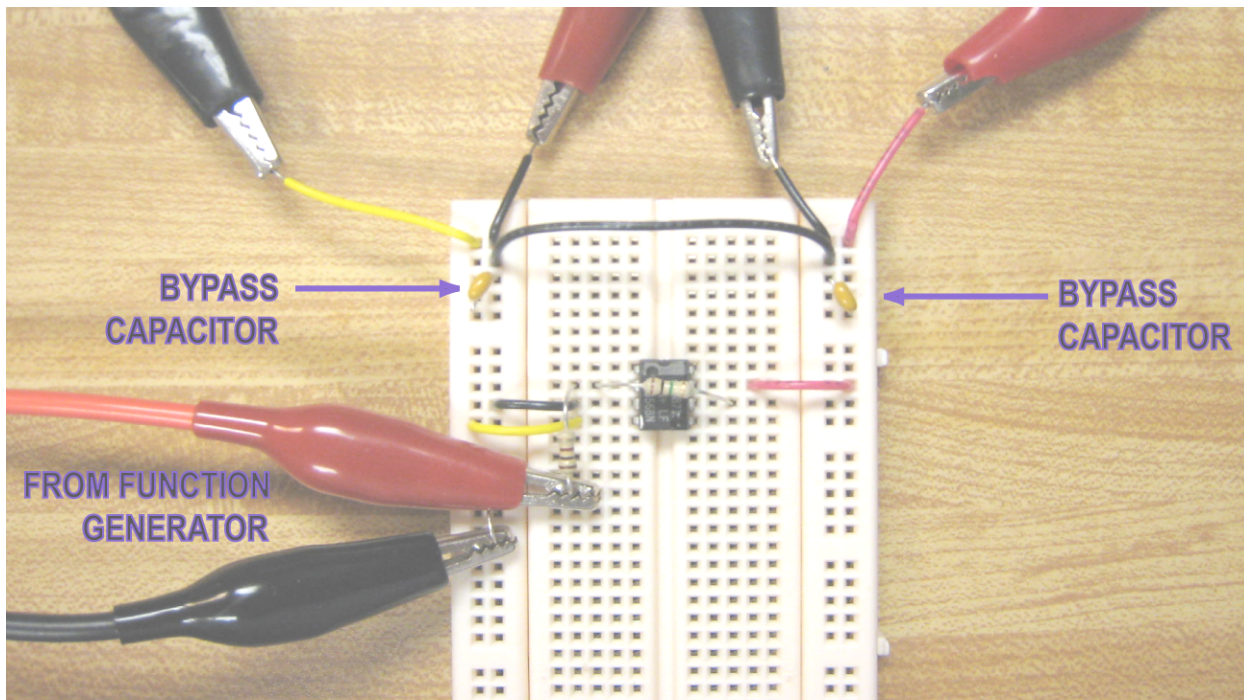
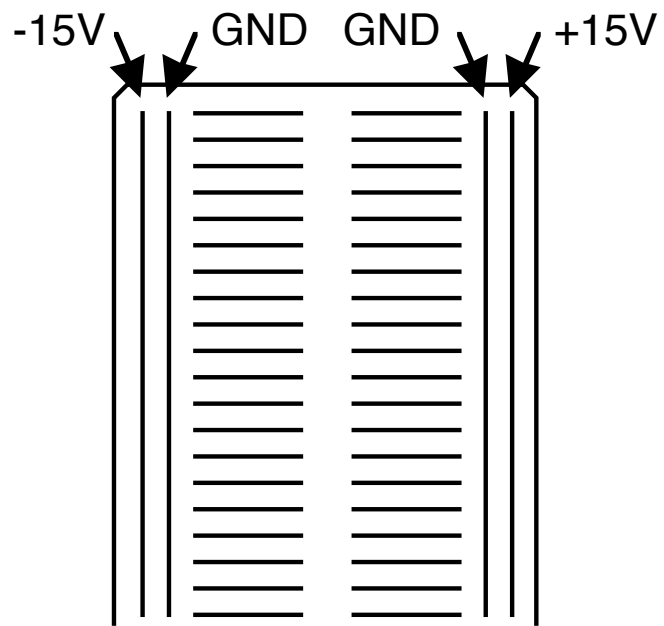
The purpose of this lab is to investigate op-amp performance in various gain configurations. We will examine how closely the LM741 op-amp approaches the ideal op-amp model.

General lab tips:

- a) Keep physical layout neat and organized, similar (if possible) to circuit diagram topology to aid in troubleshooting.
- b) Keep leads short (especially on high-impedance nodes) to avoid noise pickup. Running the supplies and ground as shown on the following page simplifies connections on your breadboard. Use bypass capacitors ($0.01\mu\text{F}$ or $0.1\mu\text{F}$) between the supply rails and ground.

See suggested breadboard configuration on following page!

- c) Measure power supply voltages at the breadboard socket before inserting ICs. Beware of excessive voltage or polarity reversal.
- d) Turn off power supplies before making circuit changes.
- e) Make sure that your oscilloscope is properly configured: use the calibration signal source on the oscilloscope to be sure the scope probe attenuation is correct (10X, not 1X) and the probe is properly compensated, etc. Double-check settings if you see an unexpected measurement result. This is one of the many good reasons to **do the prelab**: if know what to expect, you can catch mistakes early before wasting too much time in lab.
- f) **Note that the scopes in AK227 can save screen shots to a memory stick using the front panel USB port.** Feel free to use screen shots of the oscilloscope waveforms to illustrate your measurements as appropriate.



Suggested breadboard configuration.

Prelab

P1. Op-amp inverting configuration

The circuit in Figure 1.1 will be used to provide gain and increase the amplitude of the v_s voltage source. Note that v_s and R_s represent the Thevenin equivalent of the function generator; the source resistance is $R_s = 50\Omega$.

- P1.1 What is the voltage gain v_{out} / v_{IN} from the amplifier input to v_{out} ?
- P1.2 What is the voltage gain v_{out} / v_s from the signal source to v_{out} ? Note that this gain will be slightly different due to the effect of the source resistance R_s . What is the advantage of having the Thevenin source resistance $R_s \ll R_1$?
- P1.3 What would be the expected values of v_{out}/v_{IN} for $R_2 = 100\text{ k}\Omega$?

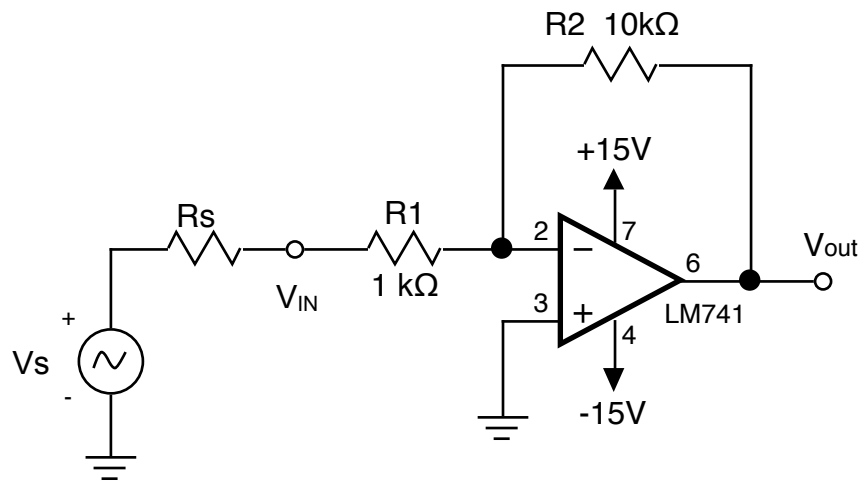


Figure 1.1

P2. Op-amp circuit design

- P2.1 Design an amplifier having a voltage gain of approximately -500, with an input impedance of $1\text{ k}\Omega$.
- P2.2 For an input sine wave of 50 mV peak at 100 Hz , what (ideally) would the output of your amplifier be?
- P2.3 For an input of zero volts DC, what (ideally) would the DC output of your amplifier be?

P3. Noninverting Amplifier Design

- P3.1 Design a high input impedance amplifier with gain of +100. To reduce power dissipation, minimum resistance value should be $1\text{ k}\Omega$.
- P3.2 Think of a simple, quick way to modify the circuit in lab to verify that the input impedance of this amplifier is greater than $100\text{ k}\Omega$. Hint: think about the general amplifier model (R_i , gain A_{vo} , R_o) we looked at in lecture, as well as in your textbook section 1.5.

Lab

L1. Op-amp inverting configuration

Construct the circuit in Figure 1.1. Before placing R1 and R2 in the circuit, use the 34405A DMM to measure the actual resistance values.

Adjust the function generator so that v_{IN} is a 100mV peak sine wave at a frequency of 100Hz.

Note: The AFG3021 function generator's amplitude readout assumes you are terminating the output in a 50Ω load to ground. Since this is not the case in any of the circuits you will be building in this lab, you need to modify the internal setting of the function generator. Using the menu buttons, select

Top Menu > Output Menu > Load Impedance

and select the "High Z" option.

- L1.1 Use channels 1 and 2 of the oscilloscope to measure v_{IN} and v_{out} . Measure the amplitudes and determine the approximate voltage gain from v_{IN} to v_{out} . Be sure to observe the sign (phase shift) of the output relative to the input. How does the measured voltage gain compare with your prediction from prelab P1.1?

Be sure to observe the cautions regarding measuring waveform amplitudes in the "Peak-to-Peak Cautions" handout attached to this lab writeup.

- L1.2 Using channel 3, place the scope probe at the noninverting input (that is, at ground). Be sure the scope channel is DC coupled. Set the trace at the center of the screen. Compare the signal at the noninverting input to the signal from the probe connected to the inverting input, as well as to the input signal v_{in} . This should reinforce the concept of "virtual ground" in your mind.

Bandwidth measurement

- L1.3 Increase the input frequency to measure the bandwidth of the amplifier (the frequency at which the amplitude of the output has dropped to 0.707 of its low frequency value). Would the bandwidth of this amplifier be suitable for a high quality audio application?
- L1.4 Replace R2 with a $100k\Omega$ resistor, and adjust v_s for $v_{IN} = 50mV$ peak. Use the oscilloscope to measure the approximate voltage gain. How does the measurement compare with the result from prelab P1.3?
- L1.5 Measure the bandwidth of this amplifier. Is it suitable for a high quality audio application?
- L1.6 What is the general relationship between the bandwidth you measure and the maximum DC (low frequency) voltage gain?

L2. Gain of ≈ -500 Amplifier

Construct the amplifier you designed in prelab P2.1.

- L2.1 With v_{IN} retained at 50mV peak, measure the output signal. How does it compare with the ideal output from prelab P2.2? Explain what is happening. This severe nonlinear distortion is known as "clipping."
- L2.2 Measure the maximum and minimum voltage limits at the op-amp output. Compare to the data sheet specification:

Electrical Characteristics (Note 5) (Continued)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Output Voltage Swing	$V_S = \pm 15V$										
	$R_L \geq 10\text{ k}\Omega$				± 12	± 14		± 12	± 14		V
	$R_L \geq 2\text{ k}\Omega$				± 10	± 13		± 10	± 13		V

- L2.3 Using three scope channels, look at v_{IN} , the op-amp inverting input, and the output while the output is clipping. **What is happening to the "virtual ground?" THIS IS VERY IMPORTANT! TAKE SOME TIME TO THINK AND UNDERSTAND THIS!!!** Explain in your lab writeup.
- L2.4 Reduce v_{IN} until the distortion goes away. Use the scope to measure the approximate gain, and compare to the design value.
- L2.5 What is the bandwidth of this amplifier?

Transfer function measurement

- L2.6 Measure the magnitude and phase response of this amplifier by measuring the peak-to-peak input and output amplitudes, and the phase shift, at various frequencies. Use about 10 different frequencies, logarithmically spaced from about 100Hz to 100kHz. Be sure to record the actual frequency at each data point.

In your lab notebook, sketch the magnitude and phase Bode plots - do your measurements correspond to a single-pole system with 3-dB frequency measured in L2.5?

In your lab writeup, compare your measured data to the ideal Bode plot.

Bandwidth - rise time relationship

- L2.7 To measure the rise time, change the input waveform to a square wave. Consider a frequency of about 500Hz to get a good look at the output pulse edges. *See the "Rise Time Measurement Tips" attached to this lab handout.*

Measure the 10%-to-90% rise time t_r . Using this measured t_r , what is the corresponding bandwidth predicted by the $BW \cdot t_r = 0.35$ relationship? How does this compare with the bandwidth you measured in L2.5 and L2.6 above?

Note that this is usually an easier measurement technique for obtaining the bandwidth of an amplifier, since you don't have to change the frequency of the input signal source - just one measurement on the step response to get t_r gives you the information you need.

More precise gain measurement

- L2.8 For an even more precise gain measurement, use the DVM to take several data points on the DC transfer characteristic of the amplifier.

For this measurement, you want a DC input to the amplifier. Use the button to select the

More Waveform Menu > DC

option. Then the DC offset adjust will control the output DC level of the function generator.

As a sanity check, look at the output waveform on the scope to make sure there is no noise or other unwanted signal. Vary the input DC level to take about 10 data points, evenly spaced over about a -10V to +10V output range. Use the DMM to measure the DC input and DC output voltages (the Auto Range feature of the DMM should be helpful here).

In your lab notebook, plot the output vs. input for each measured data point. In your writeup, use some form of data analysis (such as linear regression) to obtain a least squares fit to the data. Plot the best fit line and the data points on the same graph to see how well the measured data corresponds to the ideal. The slope of the best fit line is the gain of the amplifier.

The offset of the best fit line will probably not be zero. This is due to the op-amp offset you will observe in the next part.

DC Offset Error

- L2.9 Disconnect the function generator and ground the amplifier input. What is the DC output of the op-amp? (Use the lowest range of the DVM; the output voltage may be of order millivolts but it will probably not be exactly zero). How does this compare with what you expect from the ideal case in prelab P2.3? Based on this measurement, what is the input referred offset voltage of your op-amp?

Note: The data you measure for offset voltage in this part should reflect the Input Offset Voltage spec from the LM741 data sheet:

Electrical Characteristics (Note 5)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Input Offset Voltage	$T_A = 25^\circ\text{C}$										
	$R_S \leq 10\text{ k}\Omega$					1.0	5.0		2.0	6.0	mV
	$R_S \leq 50\Omega$		0.8	3.0							mV

L3. Noninverting Amplifier

Construct the high input impedance, gain=+100 amplifier you designed in prelab section P3.1.

- L3.1 Measure the gain for a 100Hz, 50mV peak sinusoidal input signal. How does the measured gain compare with what you expect based on your prelab calculations?
- L3.2 Using three scope channels, compare the signals at the output and the noninverting and inverting op-amp inputs. This should reinforce the idea that the op-amp configured for negative feedback will do its best to move v_{OUT} to whatever is needed to keep the input voltages equal.
- L3.3 Using the technique you outlined in prelab P3.2, verify that the input impedance of this amplifier is $> 100\text{k}\Omega$.
- L3.4 Switch the function generator to a square wave. What is the 10% to 90% rise time of the output? Consider a frequency in the range of 2 to 5 kHz to get a good look at the output pulse edges.
- L3.5 Switch back to a sine wave. Adjust the frequency to find the 3dB bandwidth of this circuit.
- L3.6 How well do your results from L3.4 and L3.5 follow the $BW \cdot t_r = 0.35$ relation?
- L3.7 Disconnect the function generator and ground the amplifier input so that the input to your amplifier circuit is zero volts. What is the DC output of the op-amp? Based on this measurement, what is the offset voltage of your op-amp? How does this compare with your offset voltage measurement from lab section L2.9?

4. Gain-Bandwidth Product Relationship

L4.1 Make a table summarizing the measured DC (low frequency) gain magnitude and bandwidth for each of the amplifiers you constructed. What is the relationship between the low frequency closed-loop gain and closed-loop bandwidth?

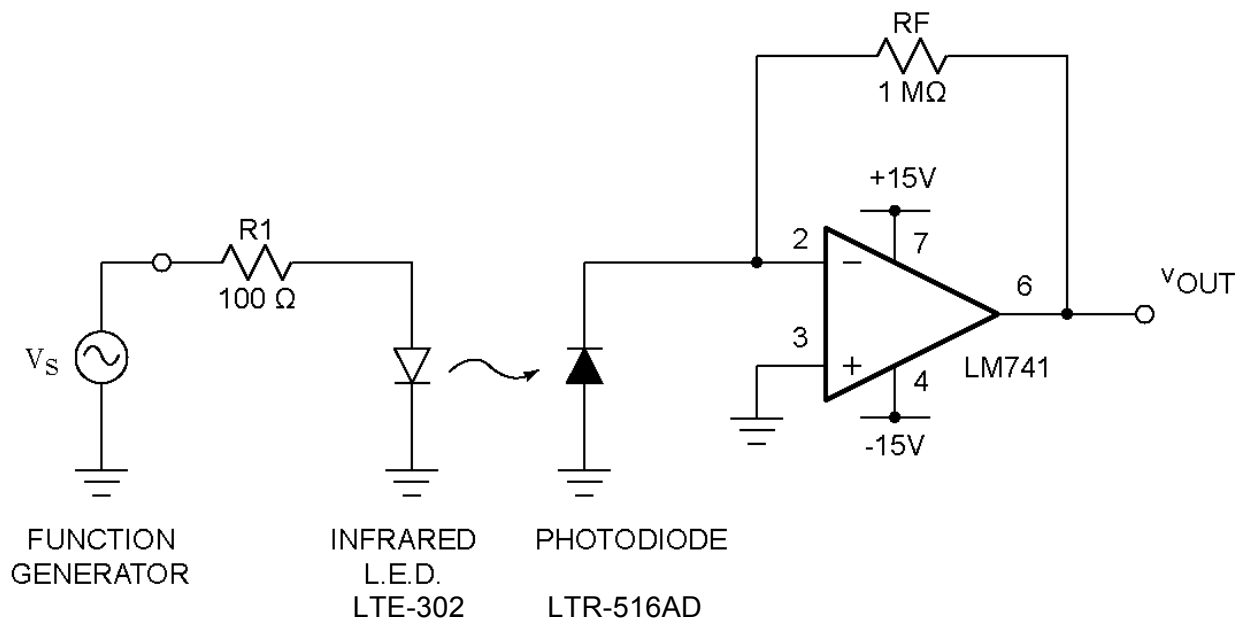
Note: The data you measure for bandwidths should reflect the unity gain bandwidth of $\approx 1\text{MHz}$ from the LM741 data sheet:

Electrical Characteristics (Note 5) (Continued)

Parameter	Conditions	LM741A			LM741			LM741C			Units
		Min	Typ	Max	Min	Typ	Max	Min	Typ	Max	
Bandwidth (Note 6)	$T_A = 25^\circ\text{C}$	0.437	1.5								MHz

4. Photodiode Amplifier

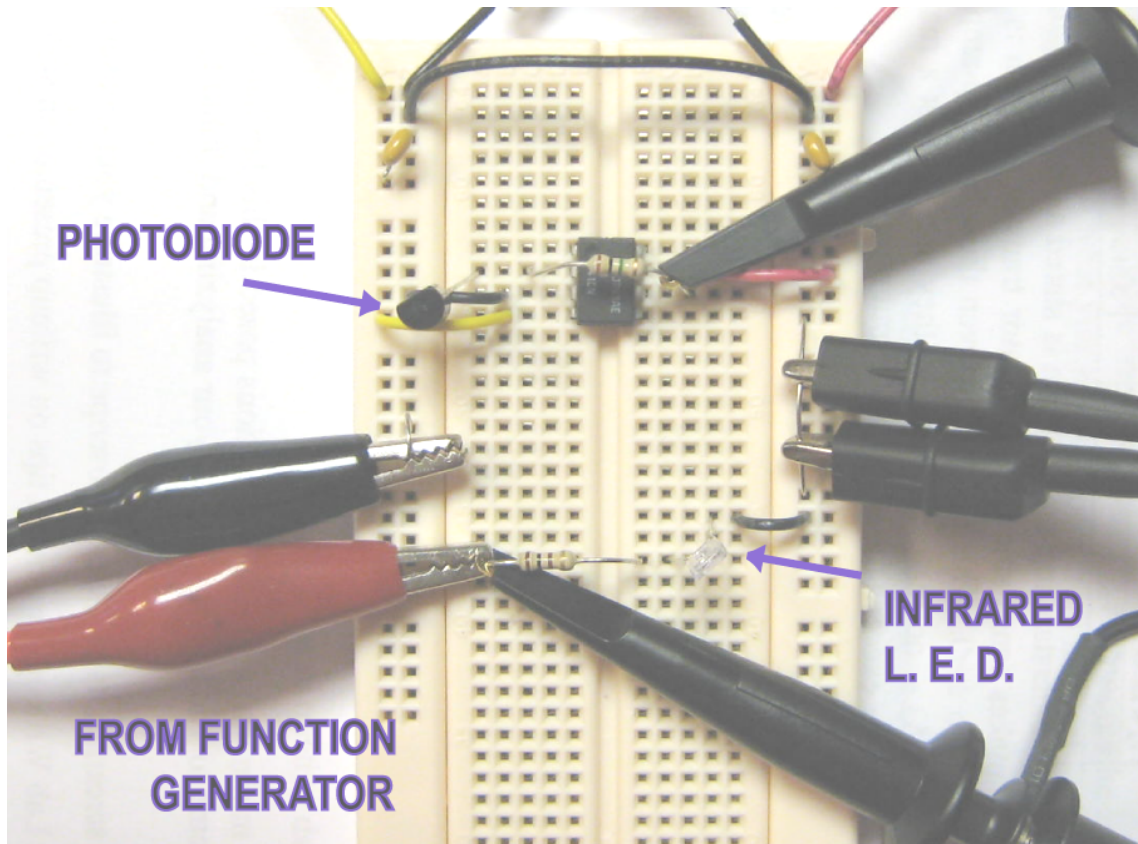
L4.1 The purpose of this part is to investigate use of the op-amp to amplify the signal from a current transducer, the photodiode. This circuit is used in data communication applications such as an infrared remote control. The circuit is shown below:



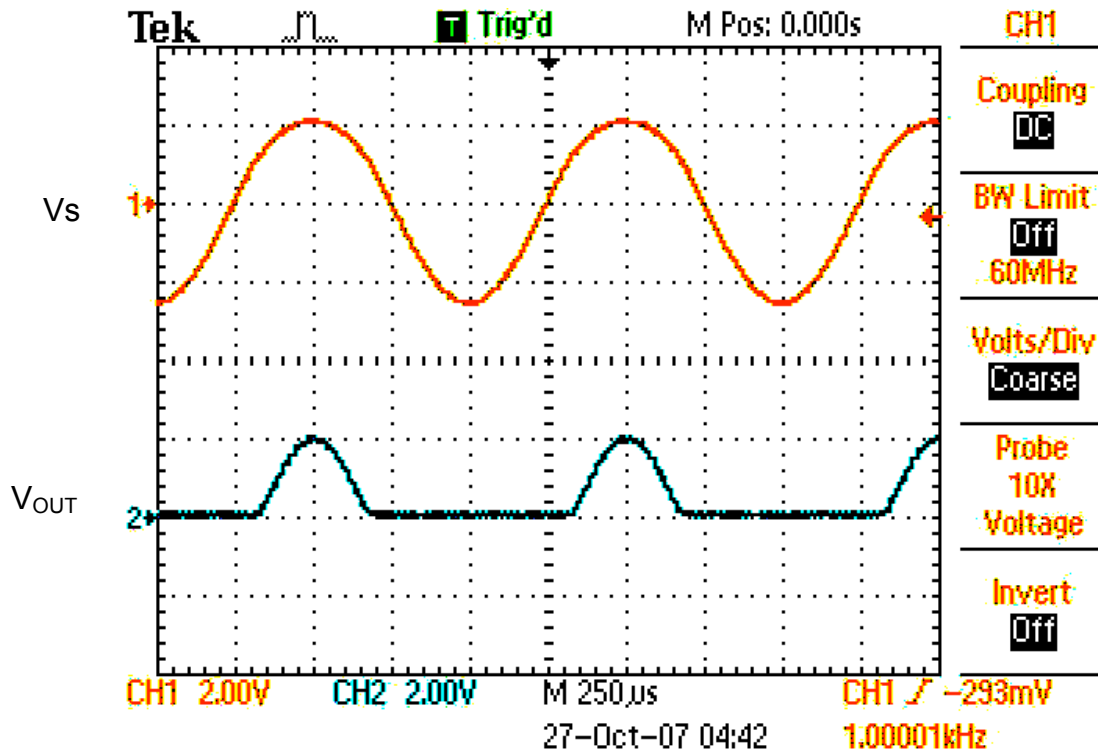
The infrared LED and photodiode are available from (and are to be returned to!) the LAB TAs.

Set up the function generator signal source to be a 2.5V peak (5V peak-to-peak) sine wave at a frequency of 1kHz.

When building the circuit on your breadboard, be sure the photodiode can “see” the IR LED (see construction example on the following page):

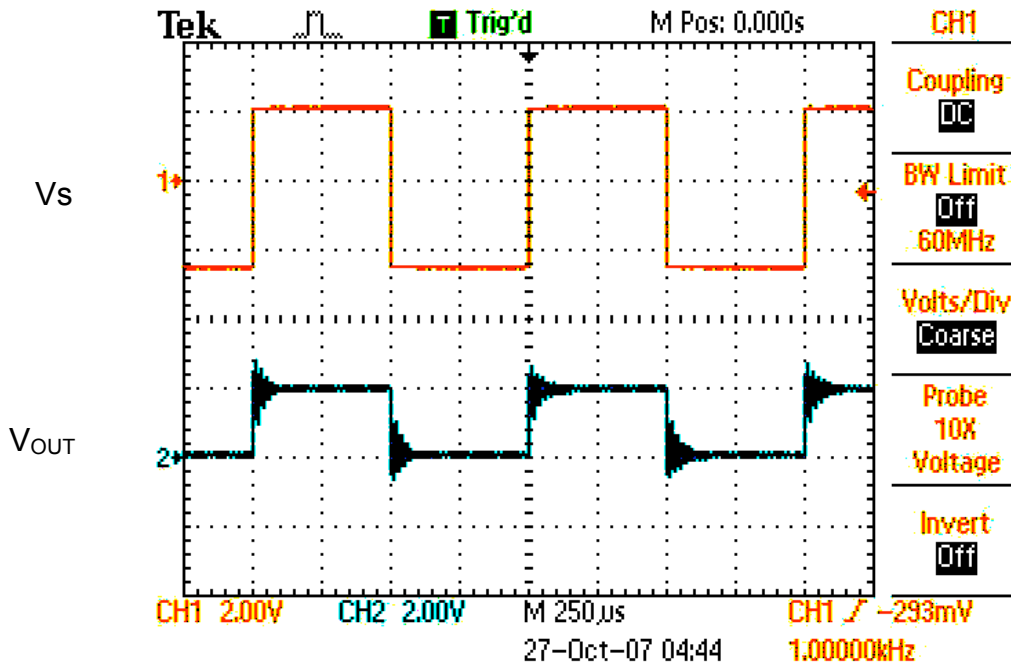


On the scope, look at the signal source voltage and the op-amp output. You should see something like this:

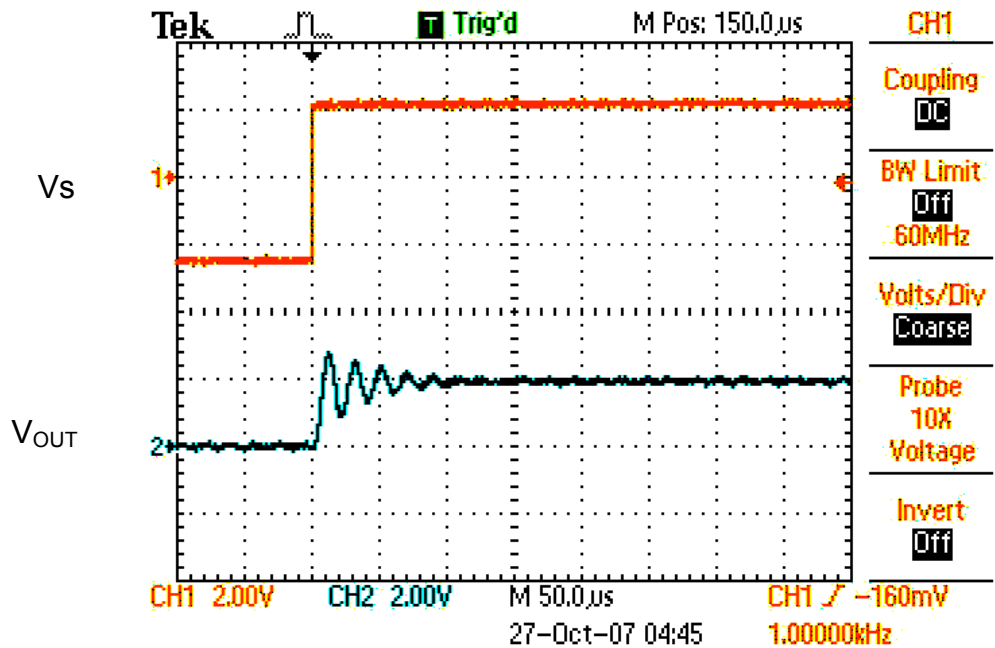


Why does only part of the sine wave get through?

In practice, this kind of link is almost always used to transmit digital data. To simulate a digital signal, change the function generator to a square wave. Now you should see something like this:



If you zoom in on the transitions of the output voltage, you will see “ringing” on the step response, a characteristic of an underdamped system:



We'll revisit this behavior in the last part of the course when we discuss stability of feedback loops ...

Lab Writeup

Organize your lab writeup in sections similar to the L1, L2, etc. of this handout.

Be sure to (at a minimum) answer any questions posed in this lab handout. Additionally, if any other insights come to you in the course of your analyzing and thinking about your data, discuss those as well.

Feel free to use screen shots of the oscilloscope to illustrate your measurements. Depending on the word processing software you are using, when you paste in the image you may wish to adjust the contrast and brightness for a better printout.

See the Sample Lab Writeup for general tips on writeup presentation style.