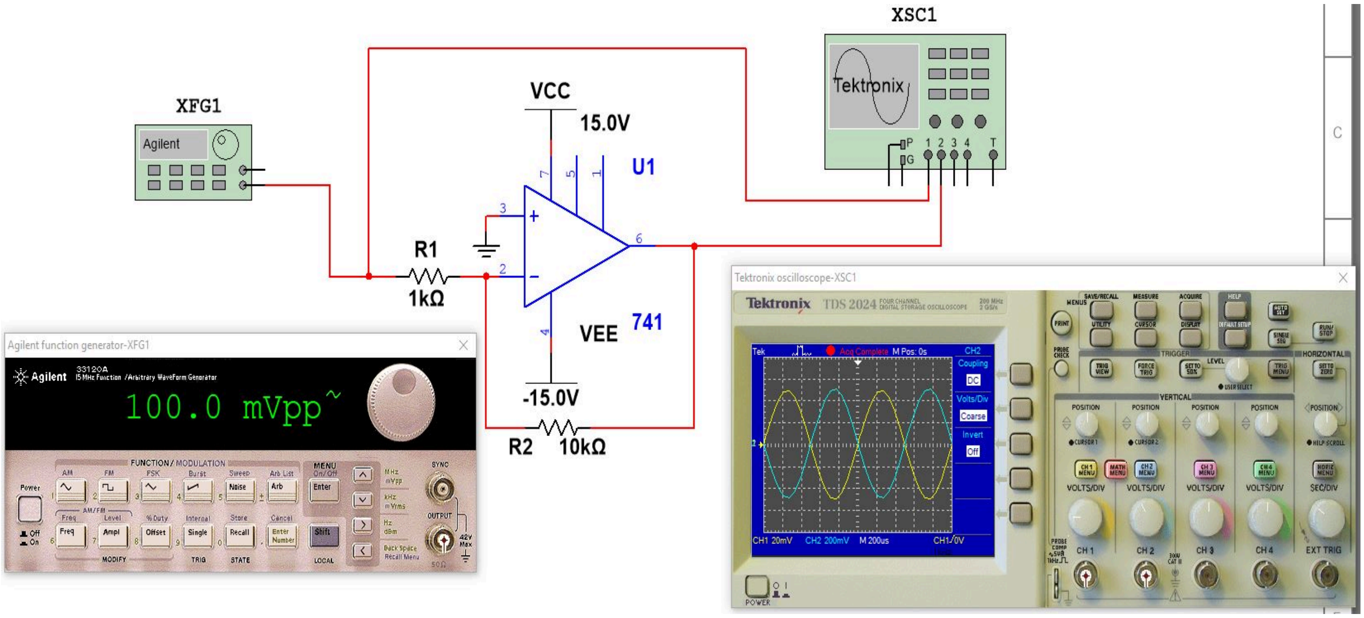
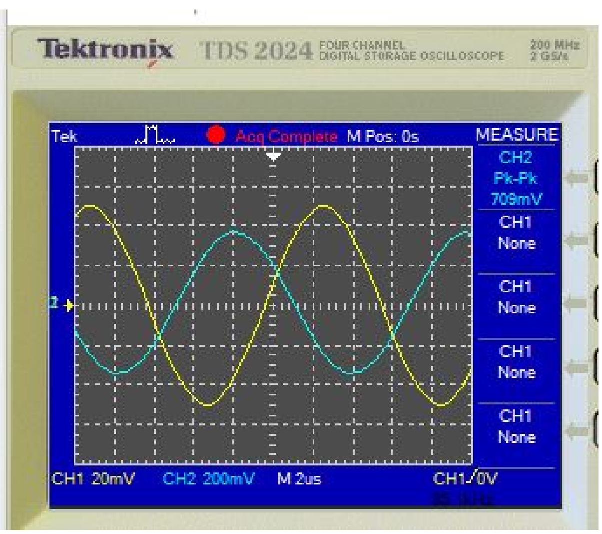
The biggest issue with op amps is the problem of frequency limitations. Using Multisim, build the following circuit and test it as follows. the Agilent Function generator is a bit difficult to work with, but we need something we can change the frequency on easily. Set it up to generate a sine wave with an amplitude of 100 mV_{p-p} and a frequency of 1.0 kHz with no DC offset.



1. What is the gain of this amplifier, from the components? -10
2. Measure the output voltage, in V_{p-p}. 1 V_{p-p}
3. What is the gain of this amplifier, from a voltage calculation? -10
4. All op amps have an upper limit to their useful frequency, so they act as Low Pass Filters. Using the output voltage, calculate the magnitude of the amplitude of the output signal you expect to see at the cutoff frequency for this circuit, in mV_{p-p} (don't worry about the phase). 707 mV_{p-p}
5. We refer to the voltage you just calculated as the "target voltage", because we will now increase the frequency until the amplitude drops to this voltage. Do that, and as you increase the frequency, adjust the oscilloscope time base so that the signal stays clearly displayed. Record the frequency when you hit the target voltage. 85 kHz. This is the cutoff frequency.

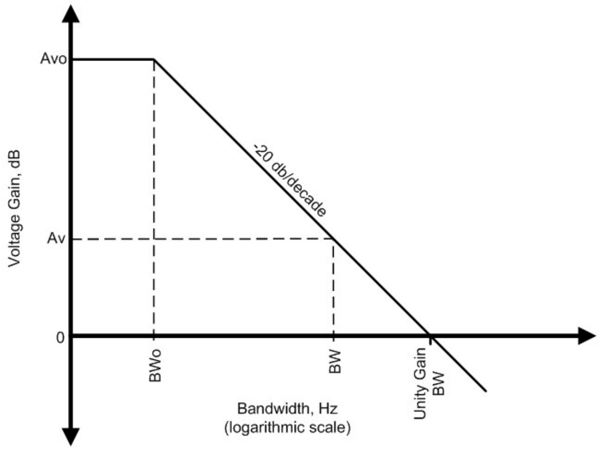
Your oscilloscope display should look something like the following:



Notice two things: First, the amplitude has dropped as closely as I can get it to the target voltage of 707 mV_{p-p}. Second, the output signal is no longer just "inverted" -- it now lags by another 45º from where it started. If we kept going, at very high frequencies it would lag by a full 90º for a single capacitor (that's from the "-j" in all of the frequency-related math that you've done in other courses).

Small Signal Frequency Limitation: Gain-Bandwidth Product

Why does the op amp act like a single-capacitor low pass filter? All high-gain circuits will go into oscillation at some frequency, so the designers of the 741 op amp have deliberately limited the output frequencies so the 741 never reaches that frequency and "goes crazy". As a result, we get the following frequency response curve, generalized for all op amps:



"BWo" is the cutoff frequency built into the device by the manufacturers.

Notice that the graph is "log-log" -- the frequency axis is a logarithmic scale, and the Gain axis is in dB, which is logarithmic.

Also notice that the Rolloff is -20 dB/decade, as expected for a single-capacitor filter.

A key point of this graph is where the line crosses the 'x' axis. At that point, the gain is 0 dB, which, in V/V gain is 1.0, or unity gain. The frequency at this point is called the "Unity Gain Bandwidth". That's the number the manufacturers report in the specification sheet as the Bandwidth. From what we saw earlier, with a Low Pass Filter that has only one capacitor, as the frequency increases by a decade (x10), the voltage decreases by 1/10th (that's the same as -20 dB/decade). In other words, the voltage decrease is always the reciprocal of the increase in frequency. So, as we increase the gain, the bandwidth, BW, decreases proportionately. As a result, the gain multiplied by the bandwidth will always be the same as the Unity Gain Bandwidth. Consequently, the Unity Gain Bandwidth is also called the Gain Bandwidth Product.

From this, we can come up with an important formula to tell us the limitations of our op amp:

BW = GBP/Av

6. From the circuit you built above, what must the Gain-Bandwidth Product (GBP) of the op amp be? 850 kHz.

On the data sheet for the 741A op amp, the "Bandwidth" is listed as 0.437 MHz. This is the Unity Gain Bandwidth or the Gain Bandwidth Product. Our result is about double what the spec sheet says, which isn't surprising -- they're giving us the worst allowable value, and they will try to aim for something considerably better.

7. Using the specified 437 kHz, what would the bandwidth limit be for an inverting amplifier with Rf = 56 kΩ and Ri = 10 kΩ? 78 kHz

8. What is the maximum gain for a 741-based amplifier that needs a bandwidth of 100 kHz? 4.37

As you can see, this seriously limits the usable gain and bandwidth of circuits using "cheap" op amps like the 741. We can, to some extent, overcome this limitation by cascading amplifiers together, because the overall gain is the product of the two amplifiers. However, when we do that, we also introduce a further limitation to the bandwidth. If we have multiple stages with the same bandwidth, the resulting overall bandwidth is reduced to

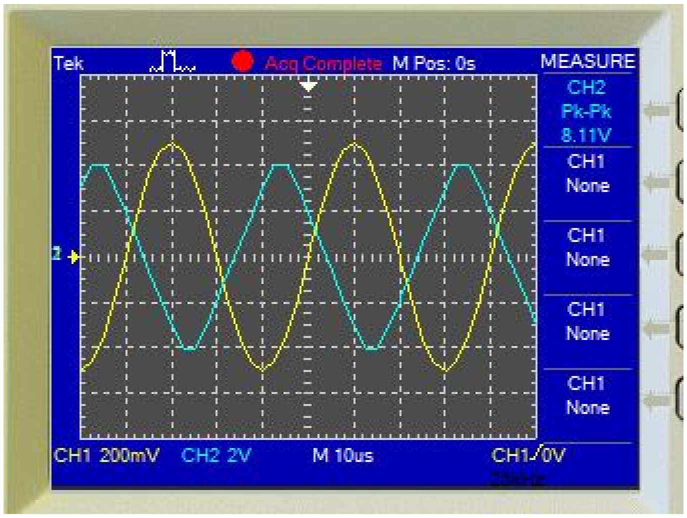
$$BW_{circuit} = BW_{stage}\sqrt{2^{\frac{1}{n}} - 1}$$

where "n" is the number of stages.

9. If we want to use two 741 op amps to get an overall bandwidth of 100 kHz, what overall gain could we get? First, use the formula to determine the Stage Bandwidth: [155] kHz. Now, use the GBP to get a single stage gain: [2.81] Finally, multiply the two gains together to get the overall gain: [7.91] At least, that's an improvement!

Large Signal Frequency Limitations: Slew Rate

If you think that the small-signal limitations were an issue, it's only part of the problem. Using the circuit above, set up the function generator to produce a 1.0 $V_{p\text{-}p}$ sine wave at 1.0 kHz. After adjusting your oscilloscope settings, you should see that the output is still 10x the input, and is an inverted sine wave. Now, set the frequency to 25 kHz. You should now be seeing something like this:



What happened to our nice sine wave?!?

The problem we're seeing arises from the time it takes for a signal to pass through the op amp. Because of all the circuitry in the op amp, the rate of change of the output voltage is limited. Whenever the input signal requires a more rapid change than this maximum, the op amp will ignore that request and continue on its merry way at its maximum rate of change. This rate of change is called the "Slew Rate".

Try changing the input signal in Multisim to a square wave -- same result as the sine wave! Try a triangle wave input -- same result! When we hit the slew rate, the op amp turns everything into triangles. We call this Triangular Distortion, and the results are not acceptable.

10. Set the function generator back to a square wave, and stretch out one of the sloping edges until it covers the oscilloscope screen. Determine the coordinates of two points from the screen, and calculate the slope using the base SI units for voltage and time. [500000] V/s

11. This is usually reported in V/μs: [0.5] V/μs

The 741 op amp spec sheet reports this as 0.3 V/μs, so our simulated op amp is slightly better.

For those of you who are interested in the math involved in coming up with the following formula, it's just simple calculus: The instantaneous slope of a function is its derivative, and the greatest slope for a sine wave is at its zero crossing point. Simple manipulation of the derivative for a sine wave tells us the maximum slope, or the Slew Rate, is $2\pi f V_p$. Since the maximum rate of change of a sinewave depends on the amplitude of the sine wave, we call the limitation based on slew rate the **Power Bandwidth**, f_{PBW}:

$$f_{PBW} = \frac{SR}{2\,\pi V_p}$$

12. If the slew rate for our circuit is 0.5 V/μs and the output signal amplitude is 5 V_p, what is the usable power bandwidth? [15.9] kHz

13. In Multisim, make sure the input is a sine wave, and slowly reduce the frequency until you see the last indication of Triangular Distortion disappear -- in other words, when the output is a sine wave again. [15.5] kHz. This is the usable Power Bandwidth of the circuit.
14. Set your function generator back to 25 kHz. What is the maximum amplitude that would allow us to have a power bandwidth of 25 kHz? [3.18] V_p or [6.36] $V_{p\text{-}p}$ What input amplitude would produce this output amplitude? [636] $mV_{p\text{-}p}$ Set your function generator output to this value, and verify that the output is now sinusoidal.
   - (•) True
   - ( ) False

So, when it comes to op amps, we need to consider two things:

- Small Signal Bandwidth, based on the Gain Bandwidth Product,
- Power Bandwidth, based on the Slew Rate

The smaller of these two results defines the usable bandwidth of our circuit.