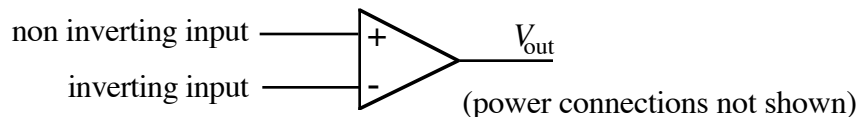


More on Operational Amplifiers (Op Amps)

Review from last week:

- Op amps are very high gain ($A \approx 10^5$) differential amplifiers.

A differential amp has two inputs (V_1, V_2) and output $V_{\text{out}} = A(V_1 - V_2)$, where A is the amplifier gain.



If an op amp is used without feedback and $V_1 \neq V_2$, then V_{out} saturates at the power supply voltage (or its maximum output swing).

Example: Assume the maximum output swing for an op amp is ± 15 V.

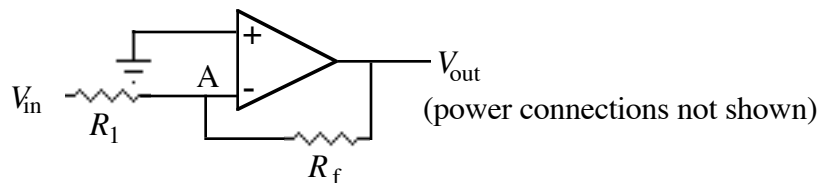
If there is no feedback in the circuit then:

$$V_{\text{out}} = 15 \text{ V if } V_{\text{non-invert}} > V_{\text{invert}}$$

$$V_{\text{out}} = -15 \text{ V if } V_{\text{non-invert}} < V_{\text{invert}}$$

- Op amps are almost always used with negative feedback. The output is connected to the - (inverting) input.

Example: Inverting Amplifier



The gain of an op amp circuit with negative feedback is determined by the feedback network (R_1, R_f in above circuit) and not the open loop gain (A) of the op amp.

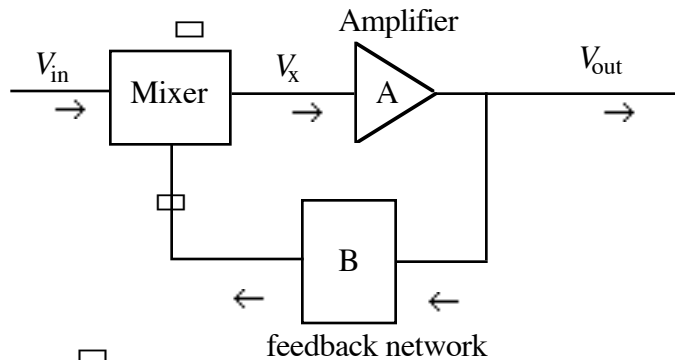
- When working with op amps using negative feedback the following two simple approximations (almost) always apply:

- 1) **No current goes into the op amp.**
- 2) **Both input terminals of the op amp have the same voltage.**

The first rule reflects the high input impedance of the op amp. The second rule is a practical consideration that is a consequence of the large open loop gain of the op amp.

Input Impedance of Op Amps and Op Amps Using Negative Feedback:

Below is general feedback circuit. Assume that the amplifier has input impedance R_{in} . We wish to find the input impedance R'_{in} of the circuit including the effect of negative feedback.



For the case of no feedback ($B = 0$) we have:

$$R_{in} = V_{in} / I_{in}$$

$$I_{in} = V_{in} / R_{in}$$

If we include negative feedback (with $B < 0$) the input to the amplifier is:

$$V_{in} + BV_{out}$$

The input current is now:

$$I_{in} = (V_{in} + BV_{out}) / R_{in}$$

From last week we saw that for the above circuit with negative feedback:

$$V_{out} = A(V_{in} + BV_{out})$$

$$V_{out} = AV_{in} / (1 - AB)$$

$$I_{in} = \frac{V_{in} + \frac{ABV_{in}}{1 - AB}}{R_{in}}$$

$$= \frac{V_{in}}{R_{in}(1 - AB)}$$

$$= \frac{V_{in}}{R'_{in}}$$

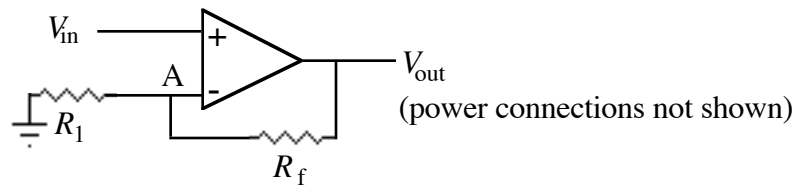
$$R'_{in} = R_{in}(1 - AB)$$

For this example the input impedance with negative feedback is *much larger* than the no feedback case.

It is also possible to lower R'_{in} with negative feedback.

- Input impedance of non-inverting and inverting amplifier:

Non-inverting amplifier:

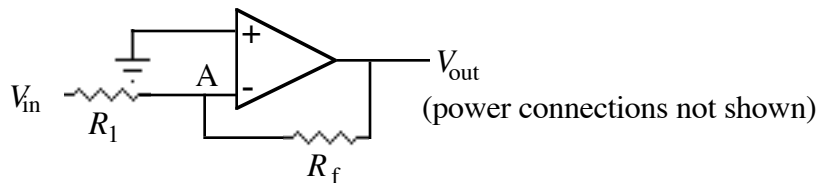


For this circuit the input voltage is directly connected to the op amp, hence the input impedance is expected to be large. The typical input resistance of a 741 op amp is $2\text{ M}\Omega$ (no feedback case). If we pick $R_1 = 1\text{ k}\Omega$ and $R_f = 50\text{ k}\Omega$ then the amplifier gain (G) is approximately 50 and $B (= 1/G)$ is 0.02. The open loop gain (A) as a function of frequency for the 741 can be read off the spec sheets. From it we can calculate the input impedance of the non-inverting amp vs. frequency:

Input impedance of non-inverting amp using $\mu\text{A}741$

f (Hz)	Open Loop Gain A	Input Impedance R_{in} (Ω)
10^1	10^5	4×10^9
10^3	10^3	4×10^7
10^6	1	2×10^6 (R of op amp)

Inverting Amplifier:



Since point A is at ground (a virtual ground) the input voltage does not actually "see" the op amp. The input impedance of this configuration is simply:

$$R_{in} = V_{in} / I_{in} = R_1$$

If we use the same resistors as in the non-inverting amplifier ($R_1 = 1\text{ k}\Omega$ and $R_f = 50\text{ k}\Omega$) then the input impedance of this amp is $1\text{ k}\Omega$, independent of frequency.

Thus the inverting amp has a low input impedance.

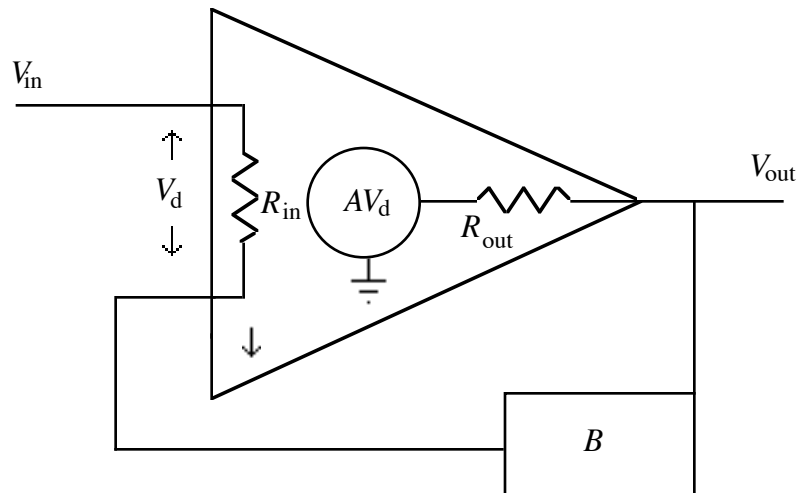
This is one of the practical drawbacks to this amplifier configuration.

Output Impedance of Op Amps Using Negative Feedback:

The output impedance of a circuit is defined as:

$$R_{\text{out}} = V_{\text{out}} / I_{\text{out}}$$

We wish to see how the above expression is modified by negative feedback.



The above figure is a model of the op amp with negative feedback.

Assume that V_{in} is grounded, and we put a voltage V at the output of the amp. The feedback network puts BV_{out} ($B < 0$ for negative feedback) back to the input. This voltage appears across the input impedance as V_d .

$$\begin{aligned} I_{\text{out}} &= \frac{V_{\text{out}} \square AV_d}{R_{\text{out}}} \\ &= \frac{V_{\text{out}} \square ABV_{\text{out}}}{R_{\text{out}}} \\ &= \frac{V_{\text{out}}(1 \square AB)}{R_{\text{out}}} \\ &= \frac{V_{\text{out}}}{R_{\text{out}} \square} \end{aligned}$$

Thus the new output impedance is *greatly reduced*:

$$R'_{\text{out}} = \frac{R_{\text{out}}}{1 \square AB}$$

and $R'_{\text{out}} \square 0$ as $A \square \bullet$.

Op Amp Stability and Compensation

One of the main reasons for using negative feedback with op amps is to make the amplifier stable against oscillations. However it is still possible to drive the amp into oscillation under certain conditions. From a previous lecture we derived the gain equation for amps with feedback:

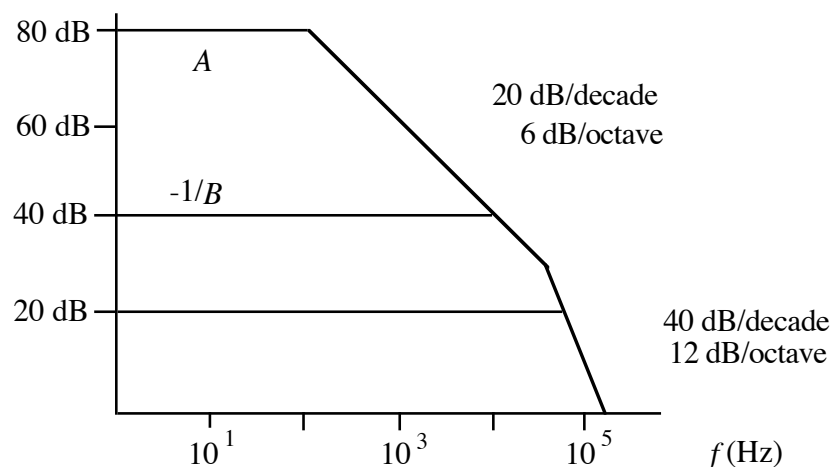
$$G = \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{A}{1 \mp AB}$$

Oscillations occur when $AB \approx 1$. This can occur for positive feedback. In principle, the inverting input of the op amp adds a fraction (determined by the feedback network) of the output to the input with a relative phase of 180° . However at high frequencies this phase shift decreases, eventually reaches zero, at which point the circuit can become unstable (i.e. oscillate). Since the op amp is made up of many resistors and capacitors we can model these phase shifts using RC networks. Recall for a low pass RC filter the gain and phase shift is given by:

$$G = \frac{V_{\text{out}}}{V_{\text{in}}} = \frac{1}{\sqrt{1 + (\omega RC)^2}}$$

$$\tan \phi = \omega RC$$

At frequencies above the break point ($\omega RC = 1$) the gain falls off as $1/\omega$. In decibels this falls off as 20 dB for each factor of 10 (or 6 dB per octave) increase in the frequency. The phase shift rapidly converges to $-\pi/2$ or -90° . The phase shift that we want to avoid is 180° . In terms of voltage gain a filter that has the gain falling off as $1/\omega^2$ will produce a 180° phase shift. The easiest way to visualize this is by imagining two low pass RC filters in series since the gains of filters are multiplicative (but additive in dBs).



The above figure is the open loop gain (A) vs. frequency curve for a "typical" op amp. For both dark lines (40 and 20 dB), the frequency (x axis) at which the lines hit the gain curve is the place where $A = 1/B$. If the phase shift at this frequency is 180° oscillations will occur. For the 40 dB line no oscillations can occur since the phase shift at that frequency must be $< 90^\circ$ since the gain rolloff is only 20 dB/decade. However oscillations can occur for the 20 dB case since gain rolloff is 40 dB/decade and a 180° phase shift is possible.

- Compensation:

It should be obvious that one way to make an op amp stable against oscillation is to insure that its open loop gain (A) falls off no faster than 20 dB/decade and thus a 180° phase shift is not possible. Some op amps (the 741 op amp for example) are *internally compensated* (with capacitors) to insure that the gain rolloff is 20 dB or smaller all the way down to voltage gains of unity. A second type of op amp is called *uncompensated* as the user is expected to add compensating capacitors external to the op amp for stability against oscillation. One advantage of the uncompensated op amp is that by a suitable choice of capacitors a higher gain than that possible from a compensated op amp is possible. On the other hand if you screw up and use the wrong capacitor(s) the circuit will oscillate!