

Lecture 8: More on Operational Amplifiers (Op Amps)

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

- Consider a general feedback circuit as shown.
 - 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:

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

- We showed last week for a circuit with negative feedback:

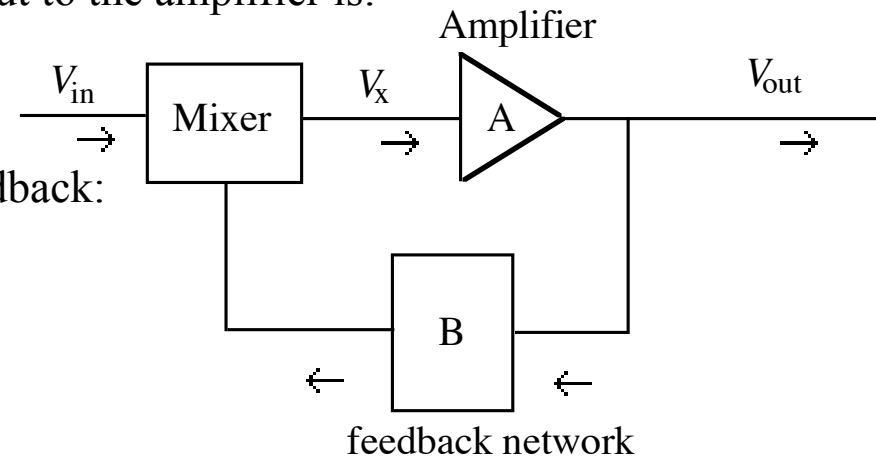
$$V_{out} = AV_{in} / (1 - AB)$$

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

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

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

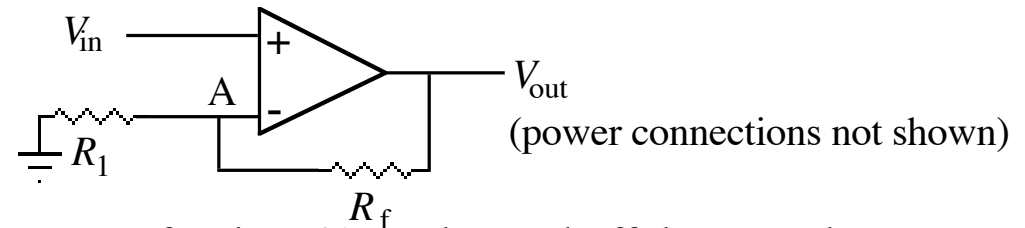
$$R'_{in} = R_{in}(1 - AB)$$



Input impedance with negative feedback is **much larger** than the no feedback case.

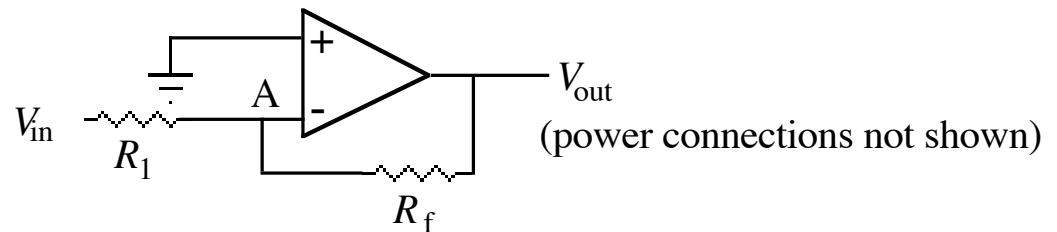
- Input impedance of non-inverting amplifier:

- ◆ The input voltage is directly connected to the op amp
 - ⇒ the input impedance is expected to be large.
- ◆ The typical input impedance of a 741 op amp is 2 MΩ (no feedback case).
- ◆ Pick $R_1 = 1 \text{ k}\Omega$ and $R_f = 50 \text{ k}\Omega$
 - ⇒ amplifier gain $G \sim R_f / R_1 = 50$
 $B = 1/G = 0.02$



- ◆ The open loop gain (A) as a function of frequency for the 741 can be read off the spec sheets.
 - ⇒ Calculate the input impedance of the non-inverting amp vs. frequency:

$f(\text{Hz})$	A	Input Impedance $R'_{\text{in}} (\Omega)$
10^1	10^5	4×10^9
10^3	10^3	4×10^7
10^6	1	2×10^6 (R of op amp)



- Input impedance of inverting amplifier:

- ◆ 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:

$$R'_{\text{in}} = V_{\text{in}} / I_{\text{in}} = R_1$$

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

◆ Assume V_{in} is grounded.

◆ Assume we put a voltage V at the output of the amp.

⇒ The feedback network puts BV_{out} ($B < 0$) back to the input.

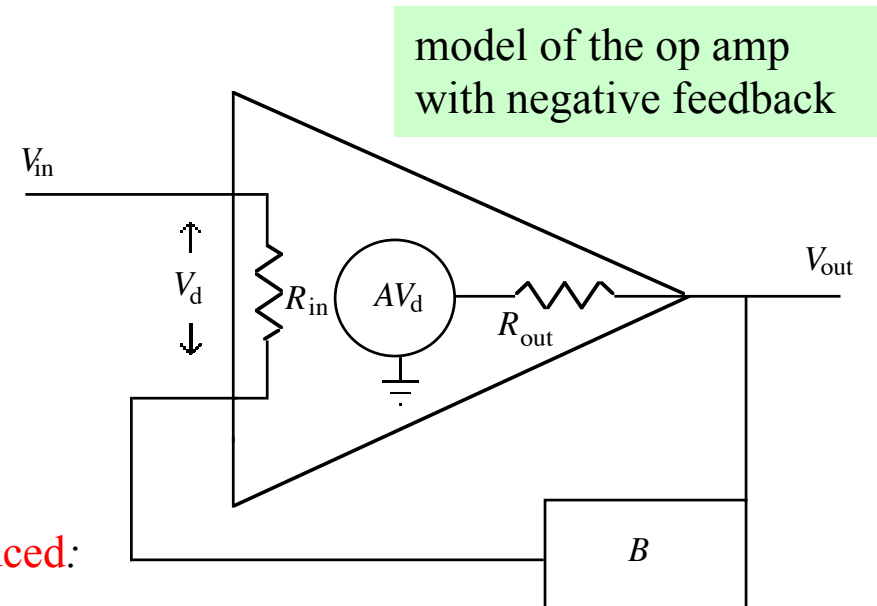
■ This voltage appears across the input impedance as V_d .

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

⇒ The new output impedance is **greatly reduced**:

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

□ $R'_{\text{out}} \rightarrow 0$ as $A \rightarrow \infty$.



Op Amp Stability and Compensation

- A major reason for using negative feedback with op amps is to make the amp stable against oscillations.
 - ◆ 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:

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

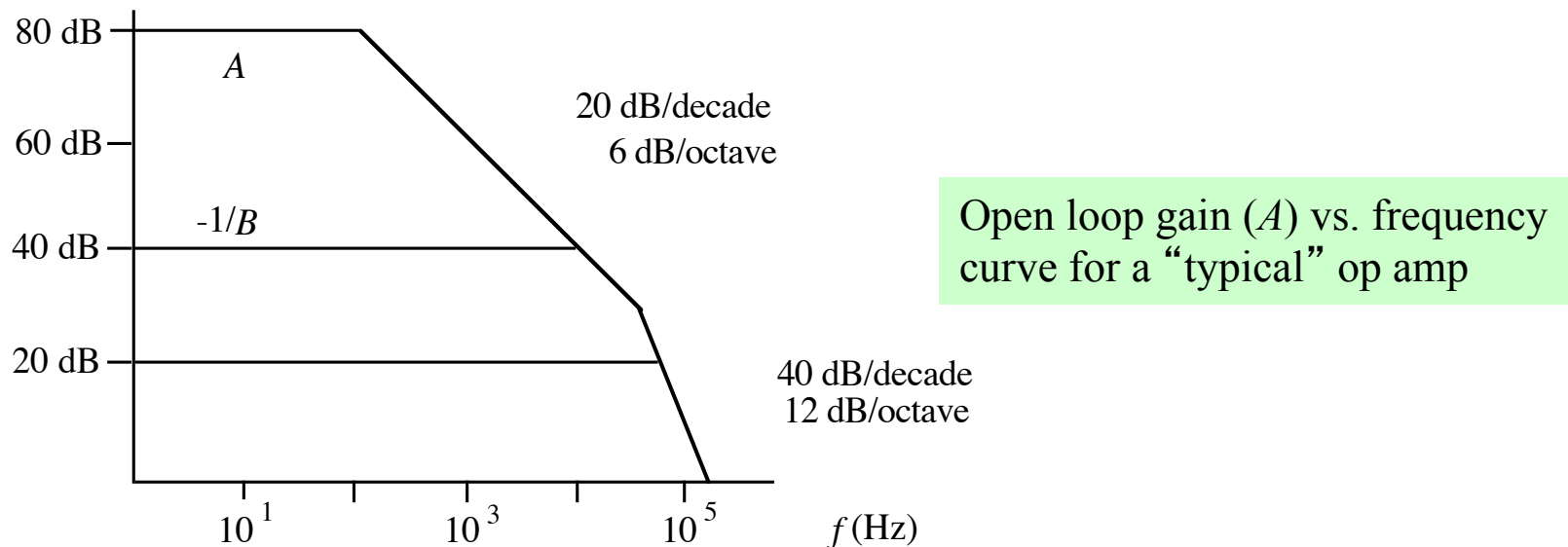
- Oscillations occur when $AB \rightarrow 1$.
 - This can occur for positive feedback.
- ◆ In principle, the inverting input of the op amp adds a fraction (determined by the feedback network) of the output to the input with a relative phase of 180° .
- ◆ However at high frequencies this phase shift decreases, eventually reaches zero
 - ⇒ 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 $1/\omega$.
- ◆ This falls off is 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 problem is by imagining two low pass RC filters in series since the gains of filters are multiplicative (but additive in dBs).



- ◆ For 20 and 40 dB lines the frequency (x axis) at which the lines hit the gain curve is 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
 - the gain rolloff is only 20 dB/decade.
 - ⇒ the phase shift $\leq 90^\circ$
- ◆ For the 20 dB line
 - oscillations can occur
 - the gain rolloff is 40 dB/decade
 - ⇒ a 180° phase shift is possible

- Compensation:
 - ◆ To make an op amp stable against oscillation
 - make insure the open loop gain (A) falls off no faster than 20 dB/decade
 - ⇒ not possible to have a 180° phase shift.
 - ◆ Some op amps (e.g. $\mu A741$) are *internally compensated* (with capacitors) to insure that the gain roll-off is 20 dB or smaller all the way down to voltage gains of unity.
 - ◆ A second type of op amp is called *uncompensated*
 - user adds compensating capacitors external to the op amp for stability against oscillation.
 - advantage: achieve higher gain by a suitable choice of capacitors
 - disadvantage: the circuit will oscillate if the wrong capacitor(s) was chosen!