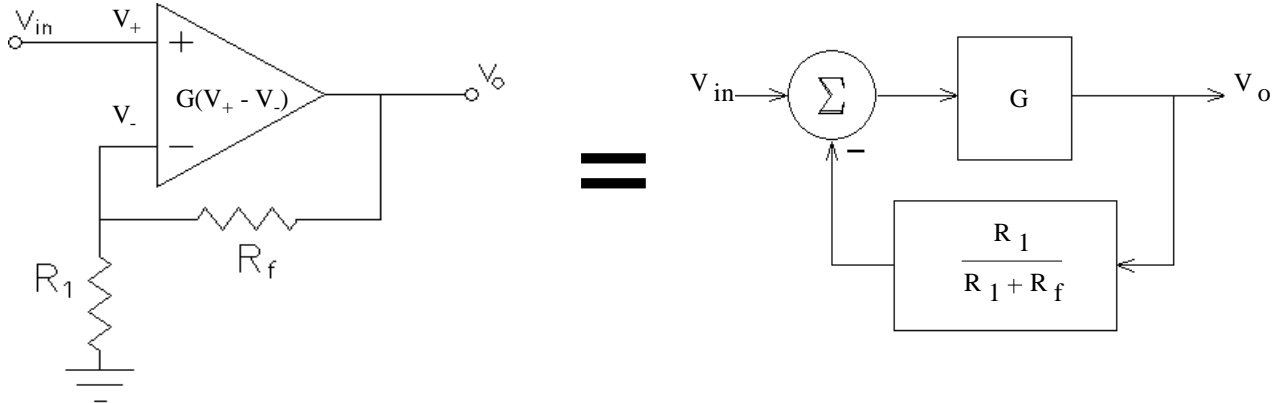


**Amplifier Compensation & Bandwidth Extension** (Especially, Op Amps)

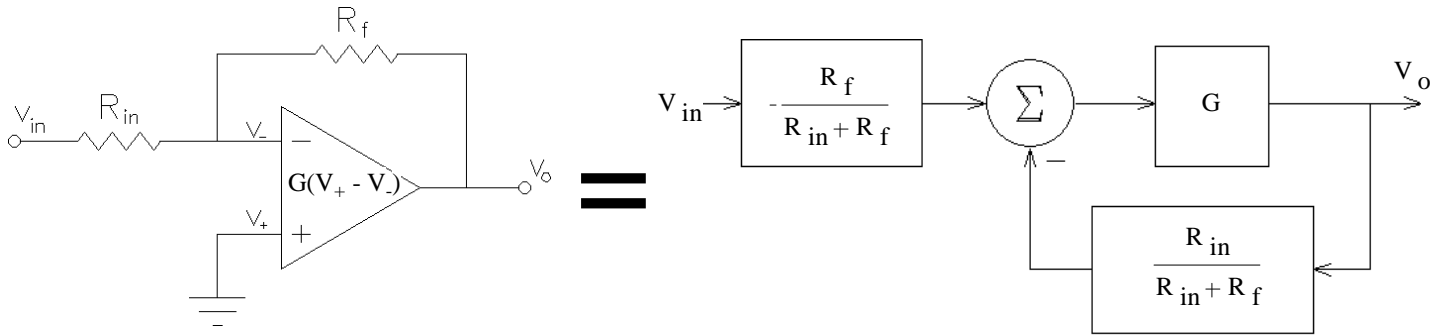
Recall from previous classes that op-amps are used with lots of negative feedback. In homework 4, you showed that common op-amp circuits could be looked at as feedback loops.



$$\frac{V_o}{V_{in}} = \frac{A}{1 + A \cdot B} = \frac{G}{1 + \frac{R_1}{R_1 + R_f} \cdot G} = \frac{G \cdot (R_1 + R_f)}{R_1 + R_f + R_1 \cdot G} = \frac{R_1 + R_f}{\frac{R_1 + R_f}{G} + R_1} \approx \frac{R_1 + R_f}{0 + R_1} = 1 + \frac{R_f}{R_1}$$

If G is very large.

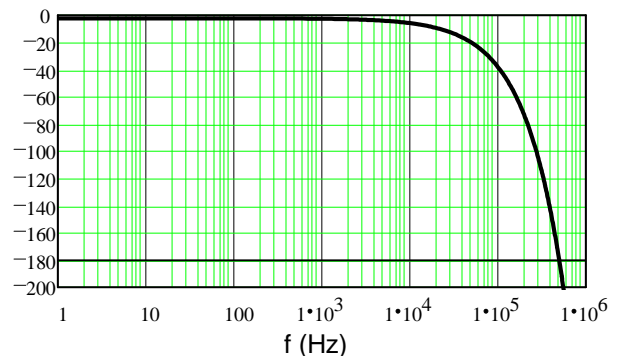
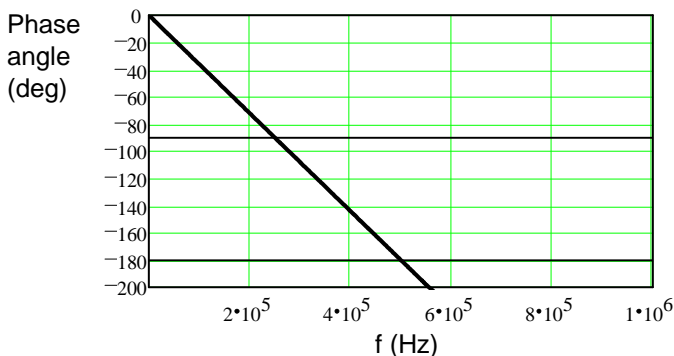
AND



$$\frac{V_o}{V_{in}} = \frac{R_f}{R_{in} + R_f} \cdot \frac{A}{1 + A \cdot B} = \frac{R_f}{R_{in} + R_f} \cdot \frac{G}{1 + \frac{R_{in}}{R_{in} + R_f} \cdot G} = \frac{R_f \cdot G}{R_{in} + R_f + R_{in} \cdot G} = \frac{R_f}{\frac{R_{in} + R_f}{G} + R_{in}} \approx \frac{R_f}{0 + R_{in}} = \frac{R_f}{R_{in}}$$

If G is very large.

But, op-amps are made of real circuitry and therefore have a little delay. Just a delay of:  $D := 1 \cdot \mu s$   
Would result phase angle plots like those below. Serious problems above 500kHz.



To make sure that op-amp circuits remain stable with feedback, they are compensated with a low-frequency pole so that the gain is less than 0dB where the phase angle falls off to -180° .

## ECE 3510 Amplifier Feedback p2

Typical op-amp compensation would look like this for an op-amp with a gain of 100k and  $D = 1\mu s$ .

$$G := 100000$$

Adequate compensation could be a pole at 2Hz ( $4\pi$  rad/sec).

Op-amp transfer function:  $\frac{G \cdot 4 \cdot \pi}{s + 4 \cdot \pi}$

$G \cdot 2 \cdot \text{Hz}$  is the gain-bandwidth product (GBW).  
(in Hz)

For the noninverting amp:

$$\frac{V_o}{V_{in}} = \frac{\frac{G \cdot 4 \cdot \pi}{s + 2}}{1 + \frac{R_1}{R_1 + R_f} \cdot \frac{G \cdot 4 \cdot \pi}{s + 4 \cdot \pi}}$$

$$= \frac{G \cdot 4 \cdot \pi}{s + 4 \cdot \pi + \frac{R_1}{R_1 + R_f} \cdot G \cdot 4 \cdot \pi}$$

new pole is at:  $4 \cdot \pi + \frac{R_1}{R_1 + R_f} \cdot G \cdot 4 \cdot \pi \approx \frac{R_1}{R_1 + R_f} \cdot G \cdot 4 \cdot \pi$  rad/sec

For the inverting amp:

$$\frac{V_o}{V_{in}} = -\frac{R_f}{R_{in} + R_f} \cdot \frac{\frac{G \cdot 4 \cdot \pi}{s + 4 \cdot \pi}}{1 + \frac{R_{in}}{R_{in} + R_f} \cdot \frac{G \cdot 4 \cdot \pi}{s + 4 \cdot \pi}} = -\frac{R_f}{R_{in} + R_f} \cdot \frac{G \cdot 4 \cdot \pi}{s + 4 \cdot \pi + \frac{R_{in}}{R_{in} + R_f} \cdot G \cdot 4 \cdot \pi}$$

new pole is at:  $4 \cdot \pi + \frac{R_{in}}{R_{in} + R_f} \cdot G \cdot (4 \cdot \pi) \approx \frac{R_{in}}{R_{in} + R_f} \cdot G \cdot (4 \cdot \pi)$  rad/sec =  $\frac{\text{GBW}}{\text{Closed-loop gain}}$  (in Hz)

The pole is also the 3dB roll-off point of the amplifier, as long as it's just a single pole.

### And, The upshot is:

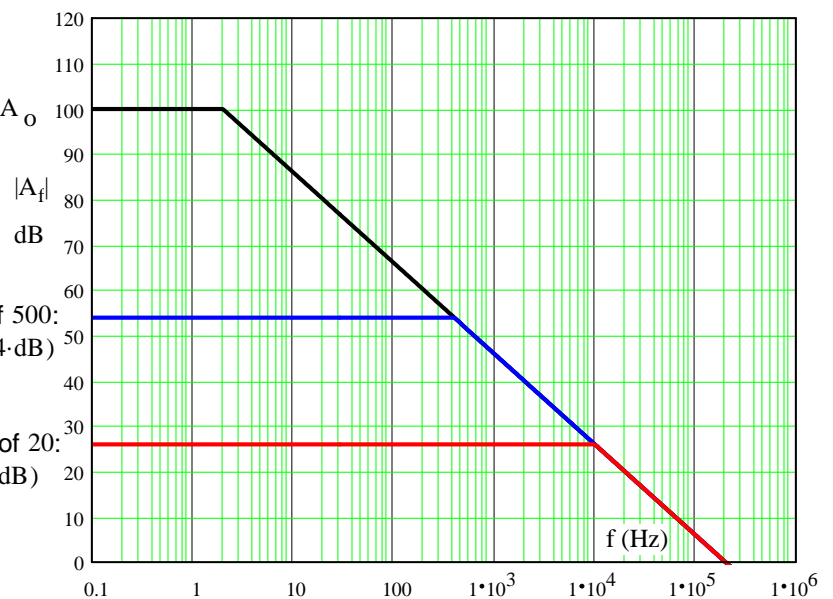
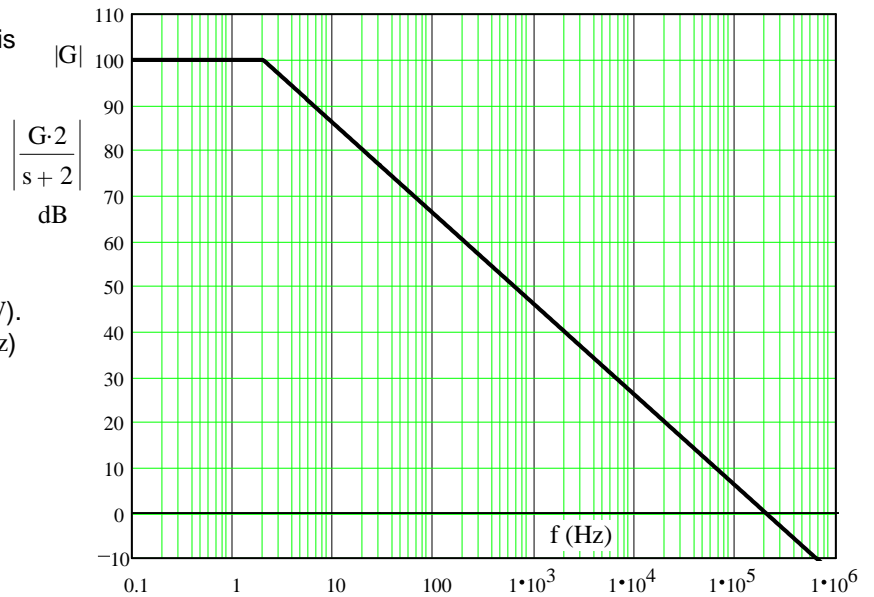
If your op-amp circuit has a closed-loop gain of "g", then the bandwidth should be about:

Closed-loop bandwidth:  $\frac{\text{GBW}}{g}$  (in Hz)

Example closed-loop frequency responses:

for a closed-loop gain of 500:  
(54-dB)

for a closed-loop gain of 20:  
(26-dB)



If you want a higher frequency response, either buy a better op-amp, with a higher gain-bandwidth product, or use more stages. However, if you use two stages with the same the 3dB roll-off point, be aware that the overall roll-off will be 6dB at that frequency and that the 3dB roll-off point will be lower by about 36%.

And about 50% lower for three stages with same 3dB roll-off point.

**Effects of Negative Feedback on Linear Amplifiers**

In general, you trade gain for other improvements, like bandwidth.

**Gain**

Closed-loop gain (Gain with feedback) =  $A_f = \frac{A_o}{1 + A_o \cdot B} = \frac{\text{Open-loop gain}}{\text{Amount of feedback}}$

If  $A_o \cdot B$  is significantly  $> 1$ , then:  $A_f \approx \frac{1}{B}$   $B$  = the feedback factor, generally less than 1, often a lot less.  
 This is a big difference between the control systems we have been studying and feedback used with amplifiers. Control systems generally use feedback closer to 1.

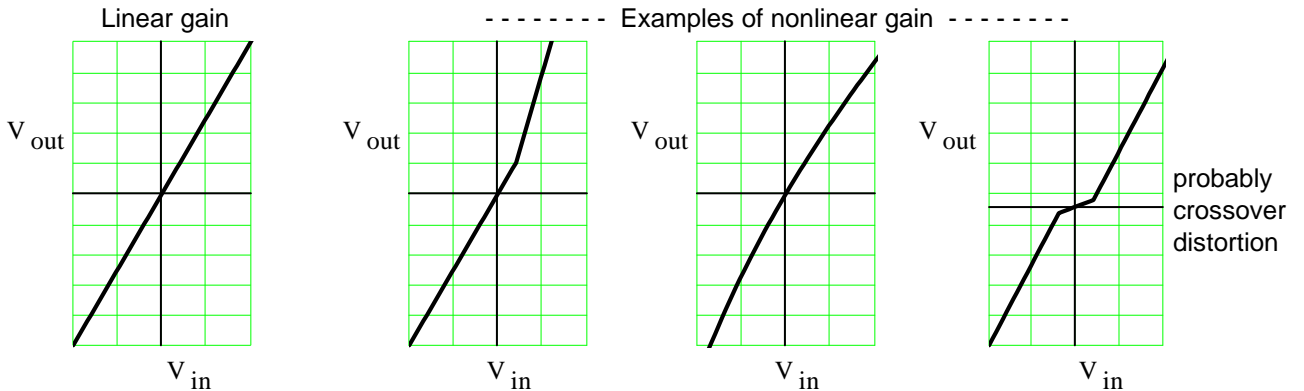
**Gain is stabilized**, even if the the open-loop gain ( $A_o$ ) in not consistent.

Possible inconsistencies:

Gain may be be inconsistent from one device to the next due to manufacturing differences.

Gain may be be inconsistent over a range of signal frequencies, as seen above..

Gain may be be inconsistent over a range of signal amplitudes and/or output magnitudes (nonlinear gain).



**Bandwidth extension**

The high-frequency side of this has already been illustrated as it pertains to op amps, but it also works for low frequencies.

in general: If the open-loop amplifier has the following transfer function:  $\frac{A_o \cdot s}{(s + \omega_L) \cdot \left(1 + \frac{s}{\omega_H}\right)}$   $A_o$  = Midband gain  
 $\omega_L$  = Low-frequency 3dB roll-off point  
 $\omega_H$  = High-frequency 3dB roll-off point

With feedback

High-frequency 3dB roll-off point =  $\omega_{Hf} = \omega_H \cdot (1 + A_o \cdot B)$  OR  $f_{Hf} = f_H \cdot (1 + A_o \cdot B)$

Low-frequency 3dB roll-off point =  $\omega_{Lf} = \frac{\omega_L}{1 + A_o \cdot B}$  OR  $f_{Lf} = \frac{f_L}{1 + A_o \cdot B}$

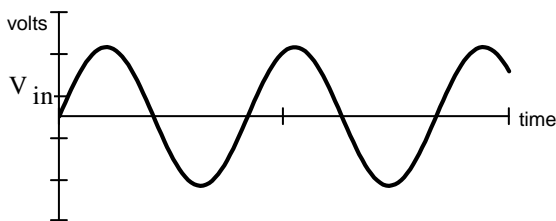
resulting closed-loop transfer function:  $\frac{A_f \cdot s}{(s + \omega_{Lf}) \cdot \left(1 + \frac{s}{\omega_{Hf}}\right)}$   $A_f$  = Midband gain  
 $\omega_{Lf}$  = Low-frequency 3dB roll-off point  
 $\omega_{Hf}$  = High-frequency 3dB roll-off point

**Noise Reduction (increase Signal to Noise (S/N) ratio)**

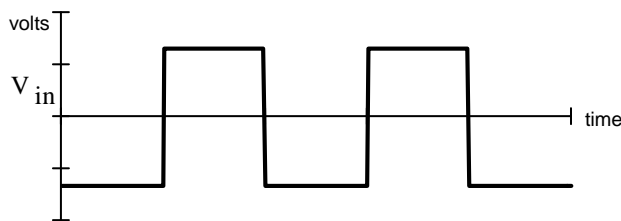
Unwanted additions to the signal, like hiss or hum, are called noise. Every amplifier stage adds some noise. Feedback can reduce noise as long as it isn't added in at the input to the first stage, where it looks just like a part of the signal. The later in the amplifier the noise is added, the more effective feedback is at reducing it.

### Reduce Signal Distortion (Total Harmonic Distortion, THD)

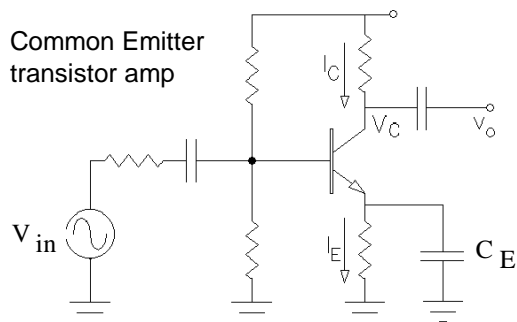
Signal distortion is usually caused by either nonlinear gain, like those shown earlier, or by the frequency response limitations which distort the relationship of the fundamental and harmonics of a signal. Noise is also a form of distortion.



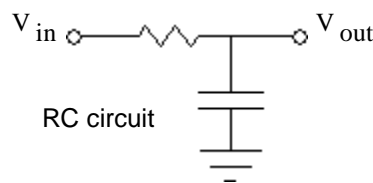
Distortion caused by nonlinear gain



Distortion caused by limited frequency response



Common Emitter transistor amp

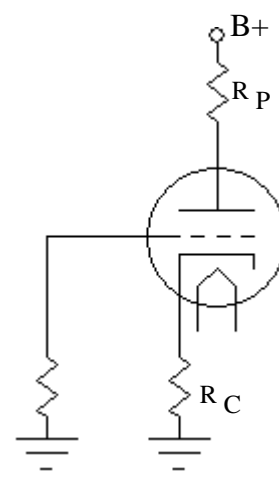
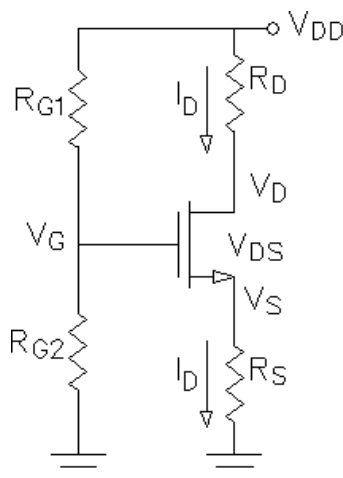
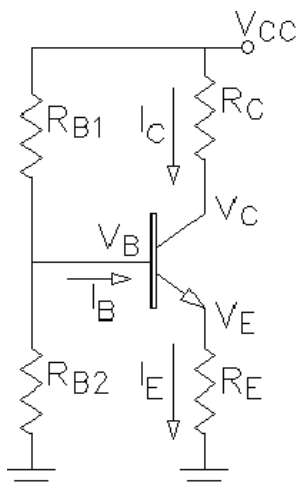


RC circuit

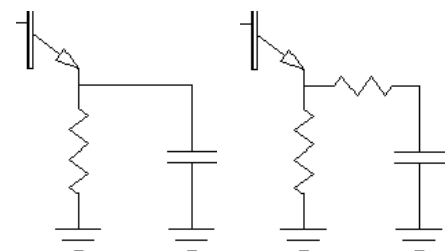
Stabilizing the gain also makes the gain more linear. Extending the bandwidth lets more harmonics through. Feedback improves both.

### Bias Stabilization

This type of feedback is part of an individual stage of an amplifier, rather than around the entire amplifier, so, in a way, it doesn't fit the discussion here. The discrete devices we use for amplification generally need to be biased into a conduction state before a signal is applied which creates current and voltage variations about the bias points. (Exceptions are class B and class D power amplifiers.)



The purpose of  $R_E$ ,  $R_S$  and  $R_C$  in each of these amplifier stages is the same. They provide negative feedback so as to stabilize the current flowing down through the device. The DC component of that current is the bias current. They all affect the signal as well, increasing the input impedance, reducing distortion and limiting the gain to about  $R_C/R_E$ ,  $R_D/R_S$ , and  $R_P/R_C$  respectively. Placing a bypass capacitor in parallel with this resistor can remove the feedback at signal frequencies, but you lose the other benefits. Partial bypass can be a compromise.

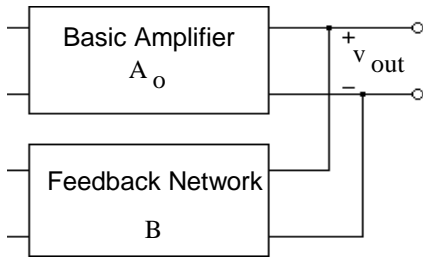


Bypass

Partial bypass

**Output Impedance**

For an amplifier with voltage feedback, the output impedance is reduced. By "voltage feedback", I mean that the feedback signal is a sample of the output voltage. Also called "shunt" feedback. (See the four feedback topologies.)

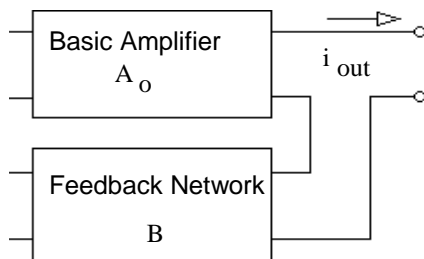


Ideally:  

$$Z_{outf} = \frac{Z_{out}}{1 + A_o \cdot B}$$

If the desired output of your amp is voltage, then a lower output impedance is exactly what you want.

For an amplifier with current feedback, the output impedance is increased. By "current feedback", I mean that the feedback signal is a sample of the output current. Also called "series" feedback. (See the four feedback topologies.)



Ideally:  

$$Z_{outf} = Z_{out} \cdot (1 + A_o \cdot B)$$

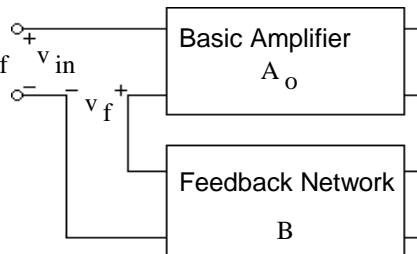
If the desired output of your amp is current, then a higher output impedance is exactly what you want.

**Input Impedance**

For an amplifier with voltage mixing, the input impedance is increased. By "voltage mixing", I mean that the feedback signal is voltage combined in series with the input voltage. Also called "series" mixing. (See the four feedback topologies.)

Ideally: 
$$Z_{inf} \cdot (1 + A_o \cdot B) = Z_{inf}$$

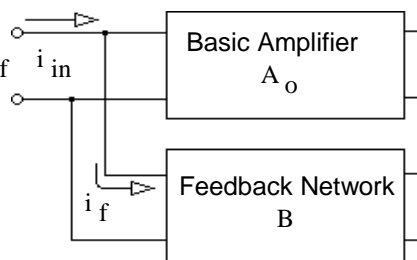
If the desired input of your amp is voltage, then a higher input impedance is exactly what you want.



For an amplifier with current mixing, the input impedance is reduced. By "current mixing", I mean that the feedback signal is a current reducing the input current. Also called "shunt" mixing. (See the four feedback topologies.)

Ideally: 
$$\frac{Z_{inf}}{1 + A_o \cdot B} = Z_{inf}$$

If the desired input of your amp is current, then a lower input impedance is exactly what you want.



Assumptions to get ideal answers:

1. Feedback networks have ideal input and output resistances.
2. Loads are ideal for the type of output.  $R_L = \infty$  for voltage outputs.  $R_L = 0$  for current outputs.

Otherwise improvements in output and input impedances will be less than ideal.

### To Find the Input Impedance

1. Draw out the full innards of all the boxes in the appropriate topology shown below, including all the non-ideal characteristics you want to include.
2. For topologies a) and d), below, connect nothing to the output, unless you want to see the effect of the load on the input impedance. Even then, it's easier to work it out without a load first and then add the effect of the load in later.  
For topologies b) and c), below, connect a short to the output, unless you want to see the effect of the load. Again, it's easier to work without a load first.

3. For topologies a) and c), below, connect an ideal voltage source to the input and find the input current. Use whatever circuit analysis methods you like.

For topologies b) and d), below, connect an ideal current source to the input and find the input voltage. Use whatever circuit analysis methods you like.

4. 
$$Z_{inf} = \frac{V_{in}}{i_{in}}$$

### To Find the Output Impedance

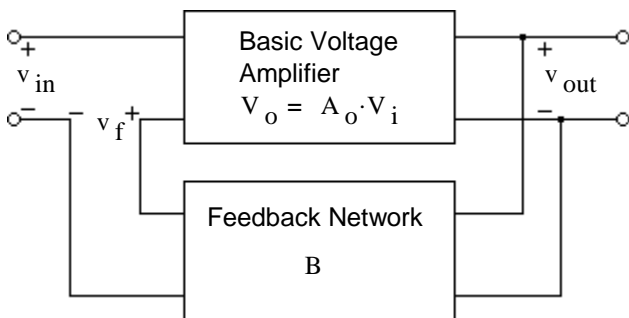
1. Draw out the full innards of all the boxes in the appropriate topology shown below, including all the non-ideal characteristics you want to include.
2. For topologies a) and c), below, connect a short at the input.  
For topologies b) and d), below, connect nothing to the input.

3. For topologies a) and d), below, connect an ideal voltage source to the output and find the current flowing back into the output.

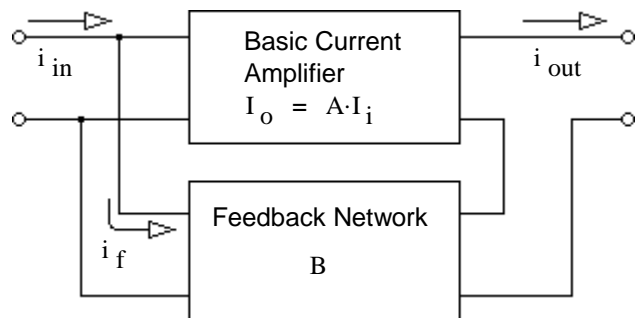
For topologies b) and c), below, connect an ideal current source to the output to force current back into the output. Find the voltage at the output.

4. 
$$Z_{inf} = \frac{V_{out}}{-i_{out}}$$

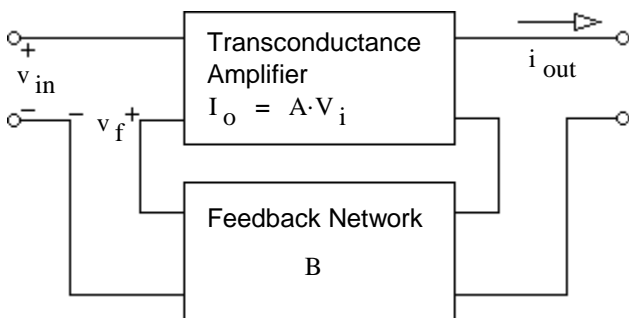
### The Four Feedback Topologies



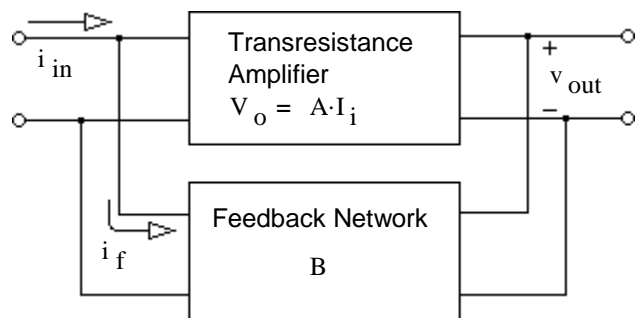
a) Voltage-mixing voltage-sampling (series-shunt)



b) Current-mixing current-sampling (shunt-series)



c) Voltage-mixing current-sampling (series-series)



d) Current-mixing voltage-sampling (shunt-shunt)

Some examples of the different topologies

a) Voltage-mixing voltage-sampling (series-shunt)

$R_e$  is the AC signal resistance from emitter to ground

Input impedance:  $R_i = R_{B1} \parallel R_{B2} \parallel \beta \cdot (r_e + R_e)$

Output impedance:  $R_o = R_C \parallel r_o$  Often neglected

AC collector resistance:  $r_c = R_C \parallel R_L \parallel r_o$

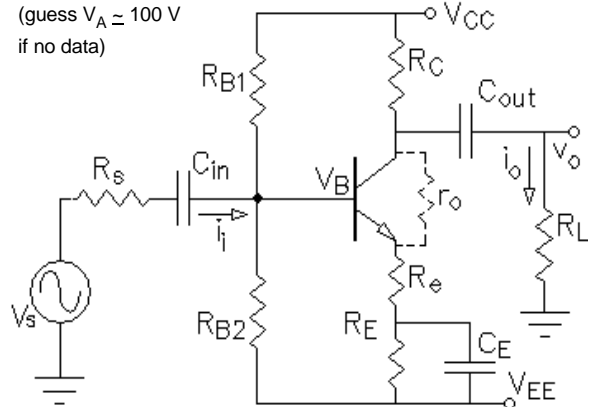
Voltage gain:  $A_v = \frac{v_o}{v_b} = \frac{r_c}{r_e + R_e}$

OR:  $\frac{v_o}{v_s} = \frac{R_i}{R_s + R_i} \cdot \frac{r_c}{r_e + R_e}$

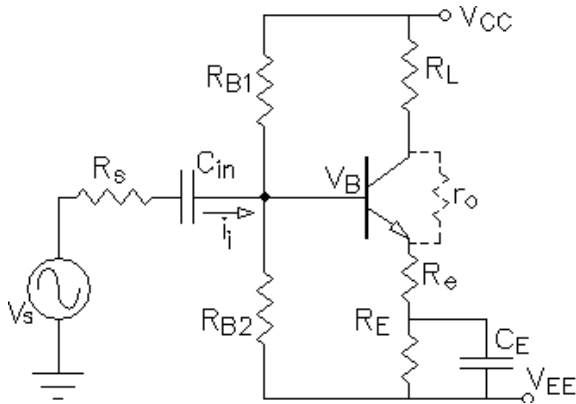
Current gain:  $A_i = \frac{i_o}{i_i} = \frac{r_c}{r_e + R_e} \cdot \frac{R_i}{R_L} = A_v \cdot \frac{R_i}{R_L}$

$R_E$  is the DC resistance from emitter to ground

$r_o = \frac{V_A}{I_C}$  Early voltage. (guess  $V_A \approx 100$  V if no data)



c) Voltage-mixing current-sampling (series-series)

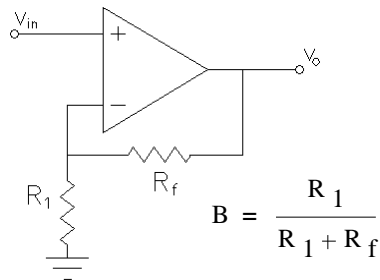


Input impedance:  $R_i = R_{B1} \parallel R_{B2} \parallel \beta \cdot (r_e + R_e)$

Output impedance:  $r_o = \frac{V_A}{I_C}$  Early voltage. (guess  $V_A \approx 100$  V if no data)

Transconductance  $g = \frac{1}{r_e + R_e}$

a) Voltage-mixing voltage-sampling (series-shunt)



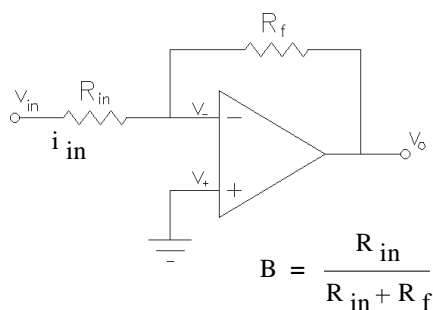
Input impedance: see op-amp data for  $R_i$

Output impedance:  $R_{outf} = \frac{R_{out}}{B}$  up to current limits of the op amp

Voltage gain:  $1 + \frac{R_f}{R_1}$

Feedback signal mixing is done within the op amp.

d) Current-mixing voltage-sampling (shunt-shunt)



Input impedance:  $R_{in}$  for voltage input

Input impedance:  $\approx 0$  for current input if you remove  $R_{in}$

Output impedance:  $R_{outf} = \frac{R_{out}}{B}$  up to current limits of the op amp

Voltage gain:  $-\frac{R_f}{R_1}$