

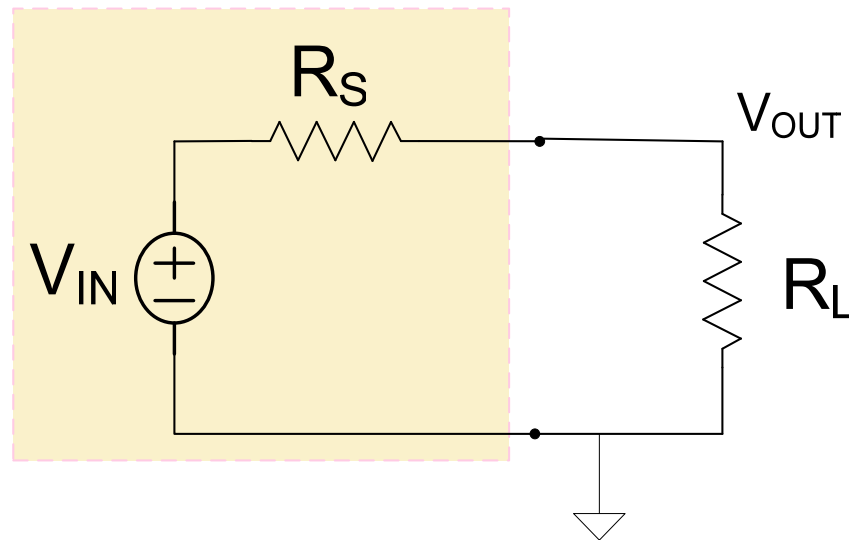
EE 230

Lecture 9

Amplifiers and Feedback

Quiz 7

A voltage source has an internal impedance of 500Ω .
What is the efficiency of the power delivered to the load if $R_L = 250\Omega$?



And the number is ?

1

3

8

5

4

?

2

6

9

7

Quiz 7

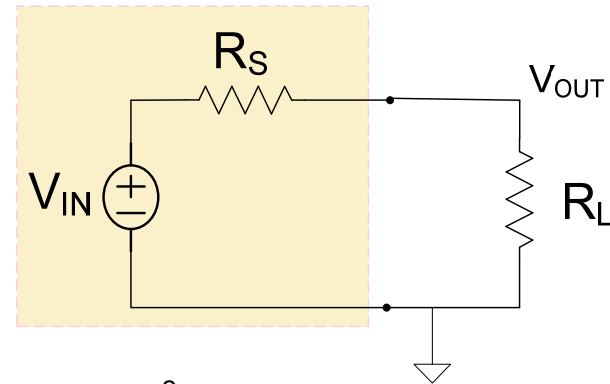
A voltage source has an internal impedance of 500Ω .
What is the efficiency of the power delivered to the load if $R_L = 250\Omega$?

Solution:

$$P_{\text{SOURCE}} = \frac{V_{\text{IN}}^2}{R_L + R_S}$$

$$P_{\text{LOAD}} = \frac{V_{\text{LOAD}}^2}{R_L} = \frac{\left(V_{\text{IN}} \left[\frac{R_L}{R_L + R_S} \right] \right)^2}{R_L}$$

$$P_{\text{LOAD}} = \frac{V_{\text{IN}}^2 R_L}{(R_L + R_S)^2}$$



$$\eta = \frac{P_{\text{LOAD}}}{P_{\text{SOURCE}}} = \frac{\frac{V_{\text{IN}}^2 R_L}{(R_L + R_S)^2}}{\frac{V_{\text{IN}}^2}{(R_L + R_S)}} = \frac{R_L}{R_L + R_S}$$

$$\eta = \frac{R_L}{R_L + R_S} = \frac{250}{500 + 250} = 0.33$$

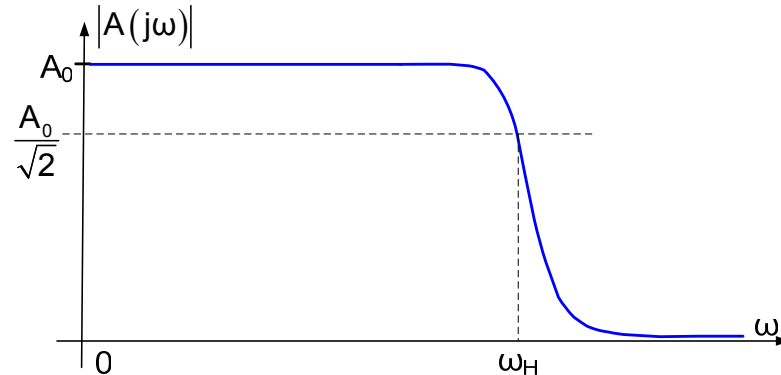
Correction of Comment Made in Lecture

The maximum efficiency of a passive network is 100%, not 50% as stated in class

Posted lecture notes should be correct

Half-power Frequency and Amplifier Bandwidth

First-Order Lowpass Amplifier



Claim: If an amplifier has a first-order lowpass response, then the half-power frequency (in rad/sec) is the magnitude of the pole

Proof:

$$A(s) = \frac{\pm A_0 p}{s - p}$$

$$A(j\omega) = \frac{\pm A_0 p}{j\omega - p}$$

$$\frac{A_0}{\sqrt{2}} = |A(j\omega_H)|$$

$$\frac{A_0}{\sqrt{2}} = \frac{|A_0 p|}{\sqrt{\omega_H^2 + p^2}}$$

$$2p^2 = \omega_H^2 + p^2$$

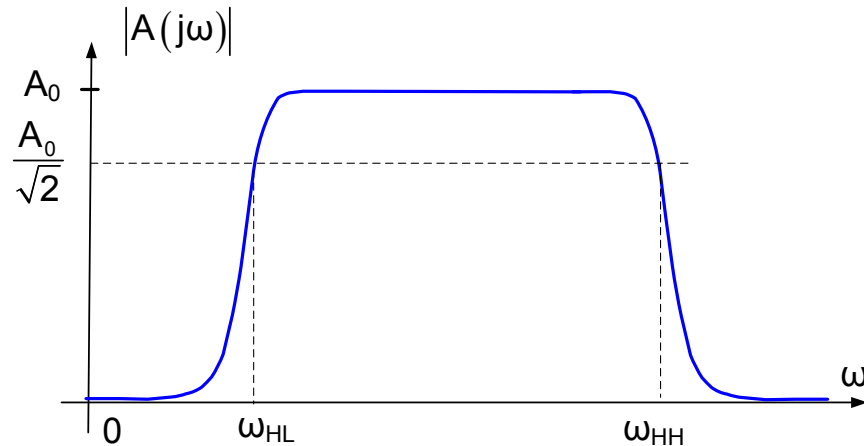
$$p^2 = \omega_H^2$$

$$\omega_H = |p|$$

$$\therefore BW = |p|$$

Half-power Frequency and Amplifier Bandwidth

Wide-band bandpass with first-order band edges



$$A(s) \approx \begin{cases} \frac{A_0 s}{(s-p_L)} \approx \frac{-A_0 s}{p_L} & \omega < \omega_{HL} \\ A_0 & \omega_{HL} < \omega < \omega_{HH} \\ \frac{-A_0}{\left(\frac{s}{p_H} - 1\right)} \approx \frac{-A_0 p_H}{s} & \omega > \omega_{HH} \end{cases}$$

$$\omega < \omega_{HL}$$

$$\omega_{HL} < \omega < \omega_{HH}$$

$$\omega > \omega_{HH}$$

Around the low-frequency transition

$$A(s) \approx \frac{A_0 s}{(s-p_L)} \quad A(j\omega) \approx \frac{j\omega A_0}{(j\omega-p_L)}$$

$$|A(j\omega_{HL})| = \frac{A_0}{\sqrt{2}} \approx \frac{\omega_{HL} A_0}{\sqrt{\omega_{HL}^2 + p_L^2}}$$

$$\omega_{HL} = |p_L|$$

Around the high-frequency transition

$$A(s) \approx \frac{-A_0}{\left(\frac{s}{p_H} - 1\right)}$$

but we found previously that

$$\omega_{HH} = |p_H|$$

Thus, the bandwidth is given by

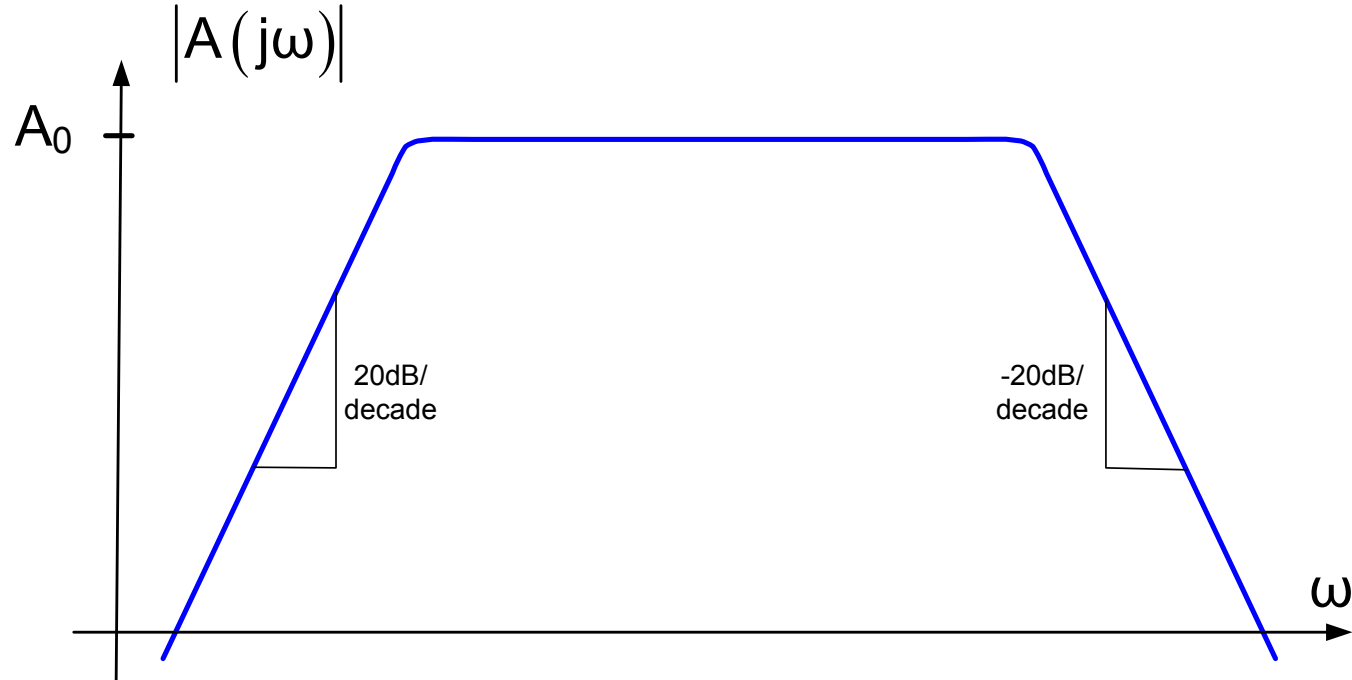
$$BW = \omega_{HH} - \omega_{HL} \approx |p_H| - |p_L| = -p_H + p_L$$

Frequency Response of Amplifiers

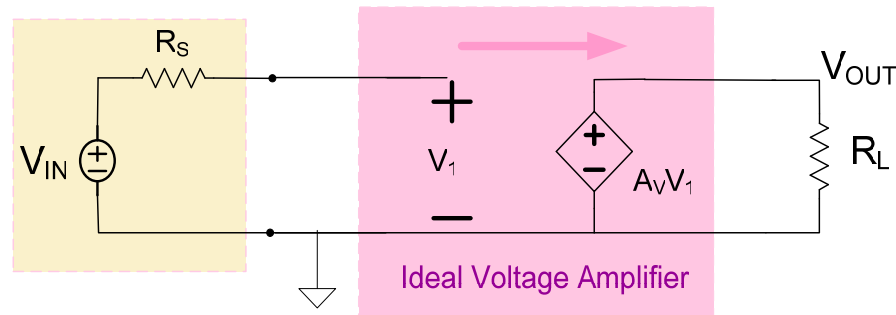
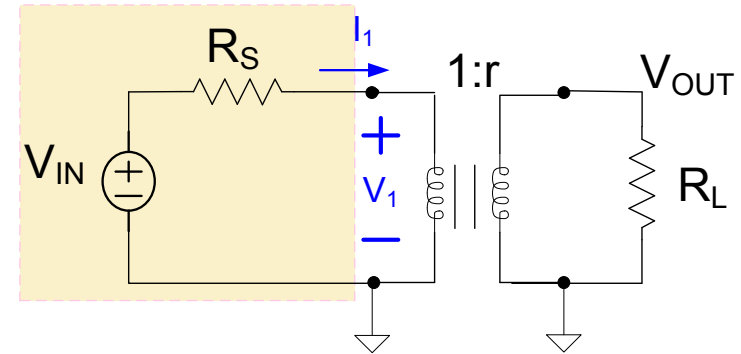
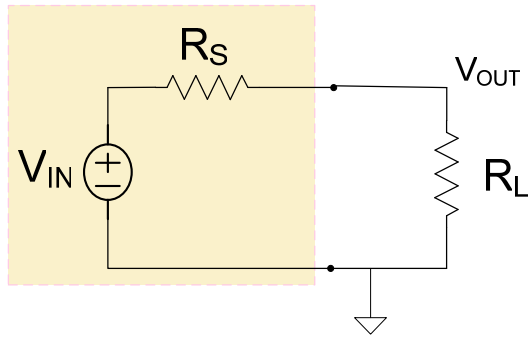
Roll-off rate of first-order amplifiers in the stop band

Wide-band bandpass with first-order band edges

Consider now the logarithmic frequency and gain axis

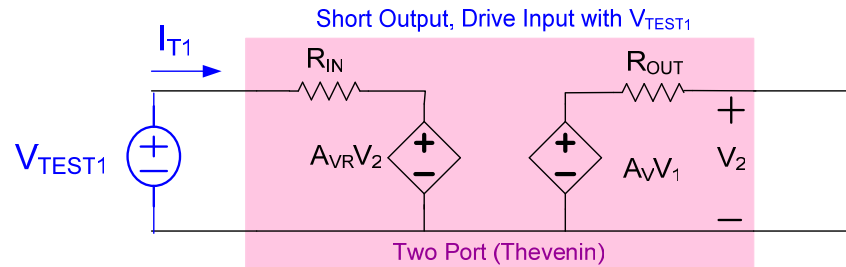
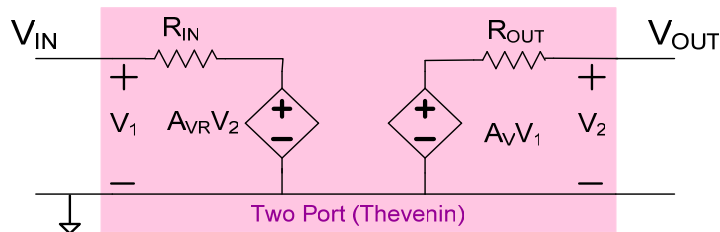
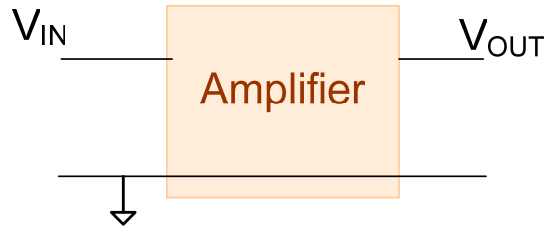


Increasing Power in a Signal with Amplifiers

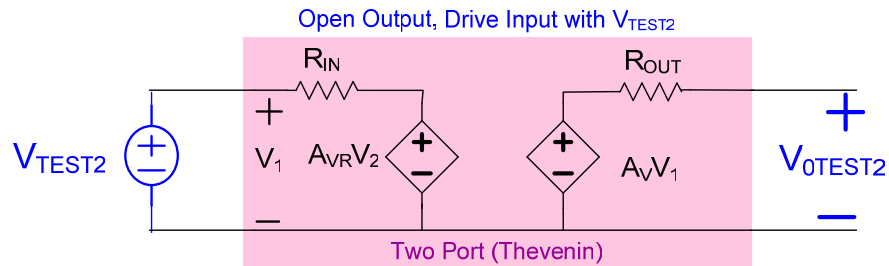


Amplifier circuits can increase the average power delivered to the load but the average power delivered to the load with any passive circuit will always be less than the power supplied by the excitation

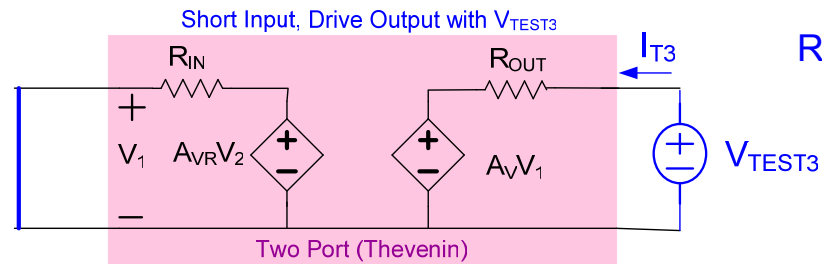
Obtaining R_{IN} , R_{OUT} , A_{VR} , and A_V in two-ports



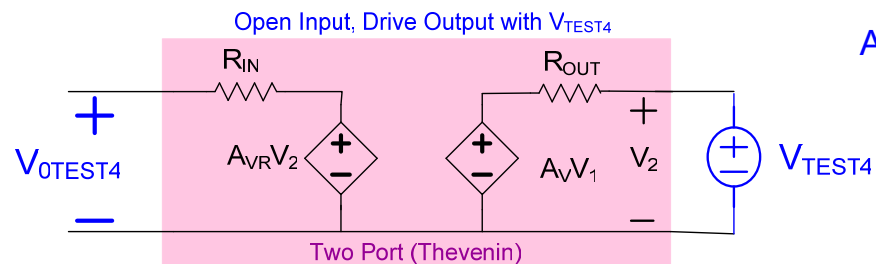
$$R_{IN} = \frac{V_{TEST1}}{I_{T1}}$$



$$A_V = \frac{V_{0TEST2}}{V_{TEST2}}$$

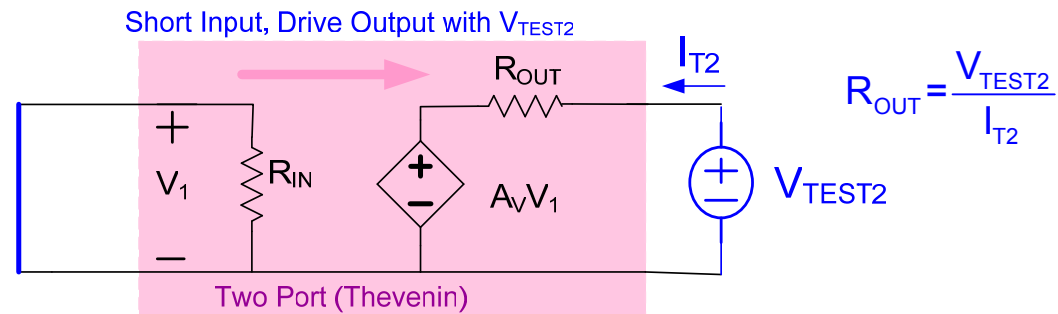
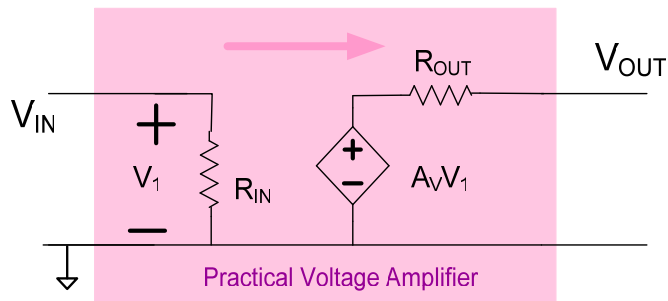
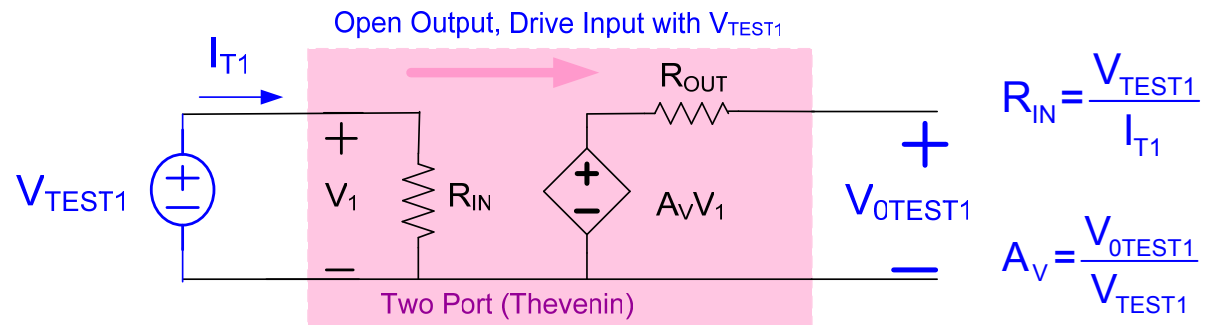
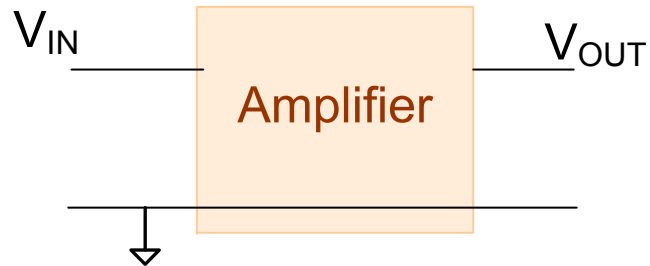


$$R_{OUT} = \frac{V_{TEST3}}{I_{T3}}$$

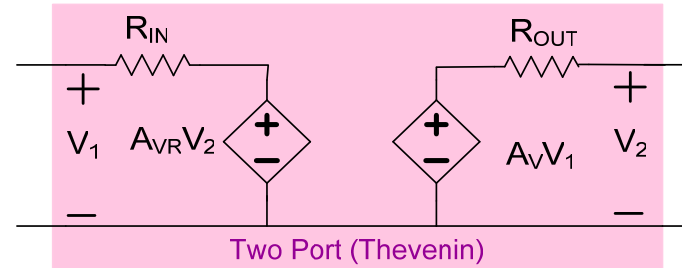
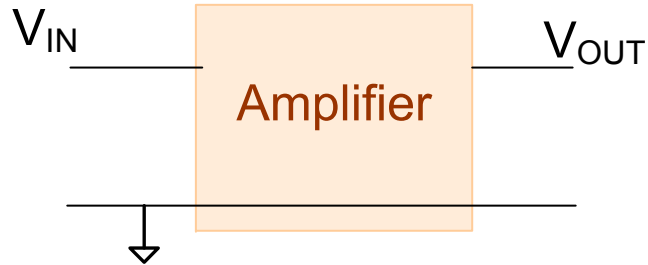


$$A_{VR} = \frac{V_{0TEST4}}{V_{TEST4}}$$

Obtaining R_{IN} , R_{OUT} and A_V in unliateral two-ports

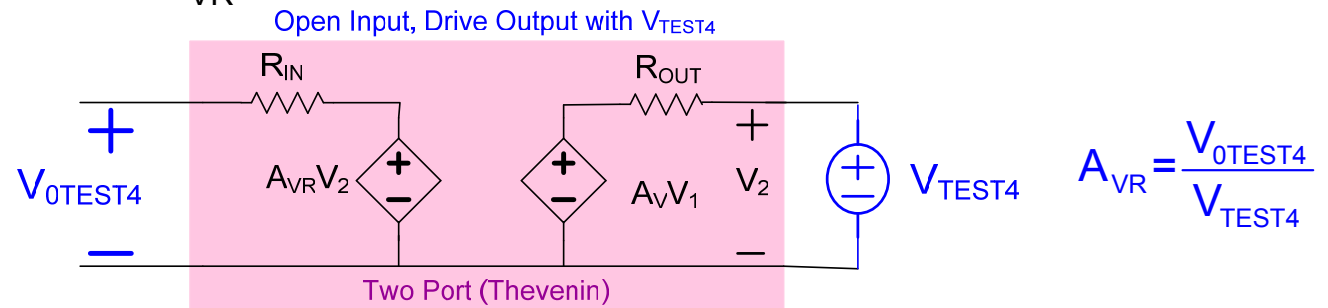


Determining whether a two-port is unilateral



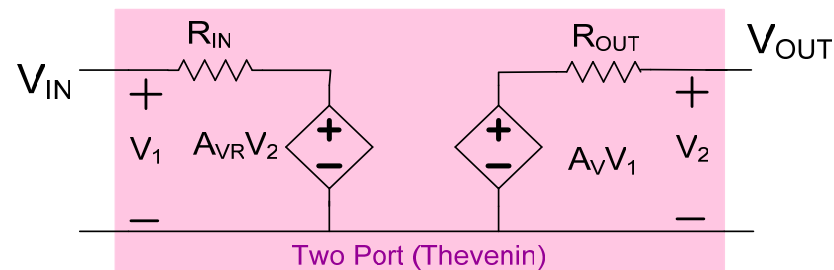
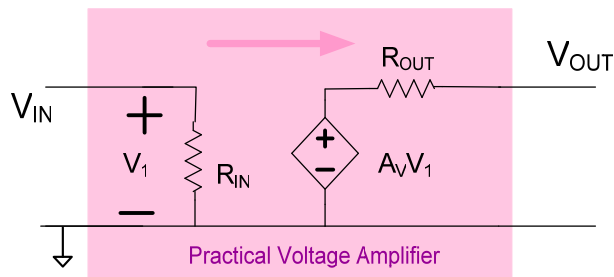
A two-port is unilateral if $A_{VR}=0$

Determine A_{VR}



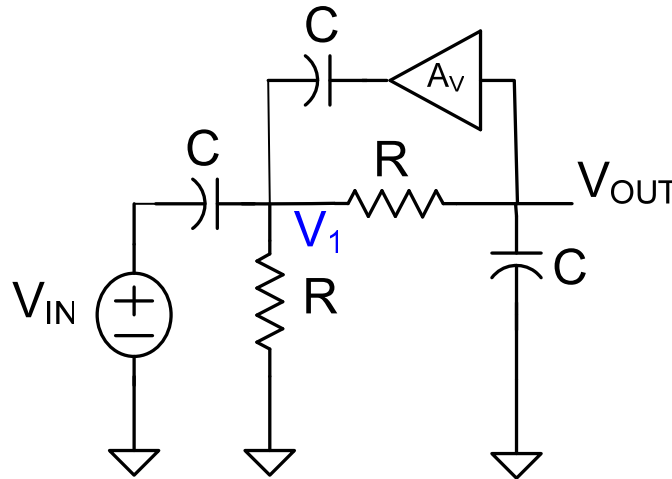
$A_{VR} = 0$

$A_{VR} \neq 0$



Moving the poles around with Amplifiers

Consider this example where a voltage amplifier (dependent source) is included in an RC network



$$V_1(s2C+2G) = V_{IN}sC + V_{OUT}G + A_V V_{OUT}sC$$

$$V_{OUT}(sC+G) = V_1G$$

$$\frac{V_{OUT}}{V_{IN}} = T(s) = \frac{s\left(\frac{1}{2RC}\right)}{s^2 + s\left(\frac{4-A_V}{2RC}\right) + \frac{1}{2R^2C^2}}$$

The poles of this circuit can be moved around by changing the gain A_V

If $A_V < 4$, this is a bandpass amplifier

If $A_V = 4$, the circuit has poles on the imaginary axis

If $A_V > 4$, the circuit has poles in the RHP

This circuit has useful properties that can not be obtained with passive circuits

Summary of Amplifier Properties

- All dependent sources are amplifiers
- Amplifiers can increase a signal voltage or a signal current
- Amplifiers can increase the power level in a signal and do not require impedance matching
- Amplifiers can have a frequency-dependent gain
- Amplifiers can be used to move the poles of a circuit into the RHP
- Amplifiers are ideally unilateral
- Amplifiers can be modeled as two-port networks
- Nonideal input and output impedance of amplifiers introduces “insertion loss”
- Amplifiers can introduce nonlinear distortion
- Amplifiers that are linear, have accurate gains, and that operate over a wide frequency range are particularly useful

Amplifiers are really useful devices !

Amplifiers – where do they come from?

It is a challenge to build amplifiers that have good linearity, accurate gains, and that operate over a wide range of frequencies

Electronic components that are used to build amplifiers

Vacuum tubes (1878)

Bipolar transistors (1948)

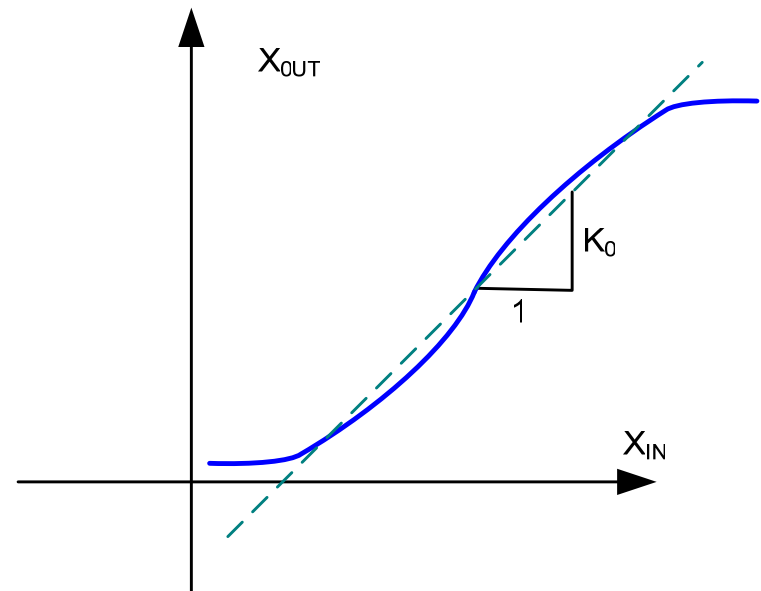
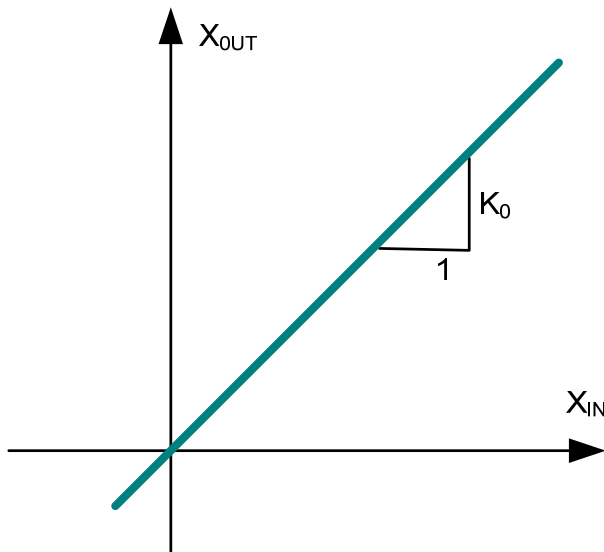
MOSFETs (~1920 conceived, ~1970 implemented)

Almost all electronic amplifiers are built with one of these three types of devices

Amplifiers – where do they come from?

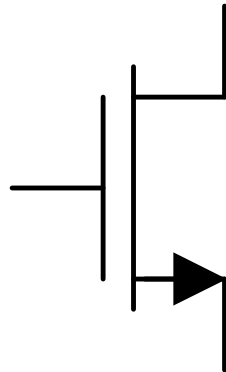
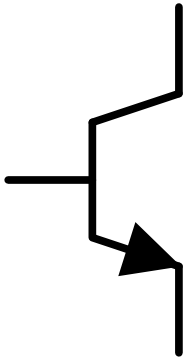
The design challenge

- Accurate Gains
- Good Linearity
- Good frequency response
- Minimal impact on insertion



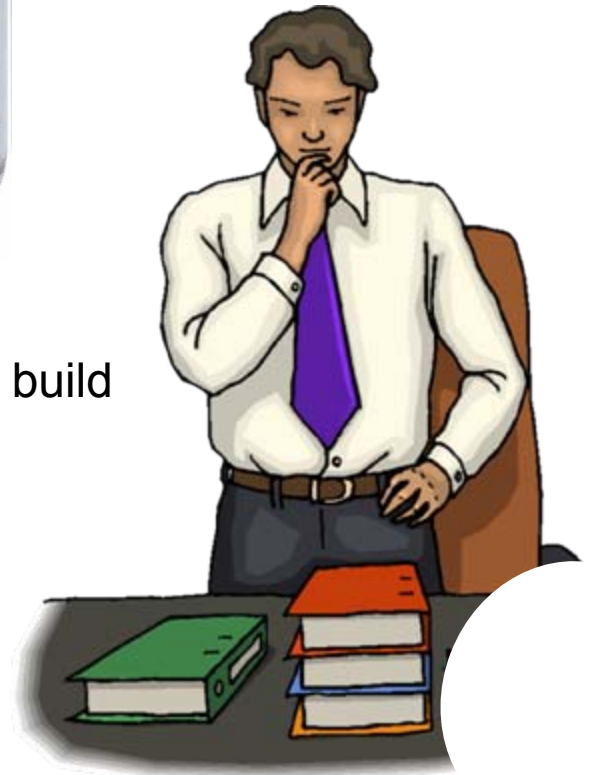
Amplifiers – where do they come from?

It is a challenge to build amplifiers that have good linearity, accurate gains, and that operate over a wide range of frequencies



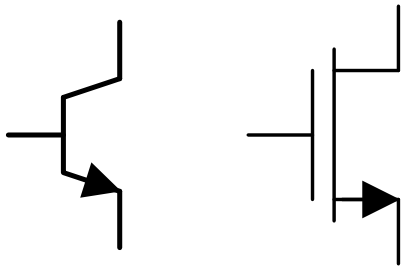
Engineers struggled for nearly 5 decades struggling to build amplifiers with

- Accurate Gains
- Good Linearity
- Good frequency response
- Minimal impact on insertion



Amplifiers – where do they come from?

It is a challenge to build amplifiers that have good linearity, accurate gains, and that operate over a wide range of frequencies



Need

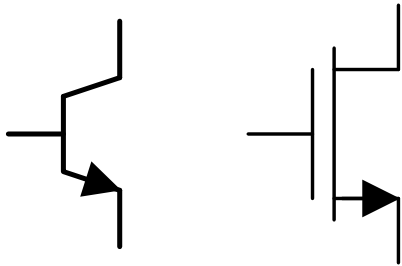
- Accurate Gains
- Good Linearity
- Good frequency response
- Minimal impact on insertion



Why can't we simply use the dependent sources discussed in EE 201 as amplifiers?

Amplifiers – where do they come from?

It is a challenge to build amplifiers that have good linearity, accurate gains, and that operate over a wide range of frequencies

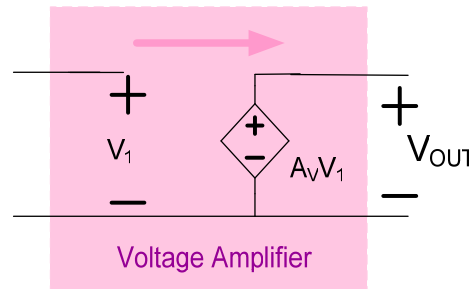
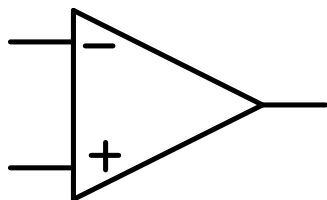


Need

- Accurate Gains
- Good Linearity
- Good frequency response
- Minimal impact on insertion



Why can't we simply use Op Amps as discussed in EE 201?



Amplifiers – where do they come from?

A major breakthrough occurred in the field of amplifier design in 1927



Need

- Accurate Gains
- Good Linearity
- Good frequency response
- Minimal impact on insertion



Harold Black, an engineer in his late '20s, introduced the concept of feedback as an alternative way to build amplifiers

He claimed (and showed) that with feedback, gain accuracy, linearity, frequency response, and several other desired properties of amplifiers ALL improved dramatically with feedback

The feedback concept for improving amplifier performance

Harold Stephen Black (April 14, 1898 – December 11, 1983) was an American [electrical engineer](#), who revolutionized the field of applied electronics by inventing the [negative feedback](#) amplifier in 1927. To some, his invention is considered the most important breakthrough of the twentieth century in the field of [electronics](#), since it has a wide area of application. This is because all electronic devices (vacuum tubes, bipolar transistors and MOS transistors) invented by mankind are basically nonlinear devices. It is the invention of negative feedback which makes highly linear amplifiers possible. Negative feedback basically works by sacrificing gain for higher linearity (or in other words, smaller [distortion](#) or smaller [intermodulation](#)). By sacrificing gain, it also has an additional effect of increasing the bandwidth of the amplifier. However, a negative feedback amplifier can be unstable such that it may oscillate. Once the stability problem is solved, the negative feedback amplifier is extremely useful in the field of electronics. Black published a famous paper, *Stabilized feedback amplifiers*, in 1934.

(from Wikipedia)



The feedback concept for improving amplifier performance

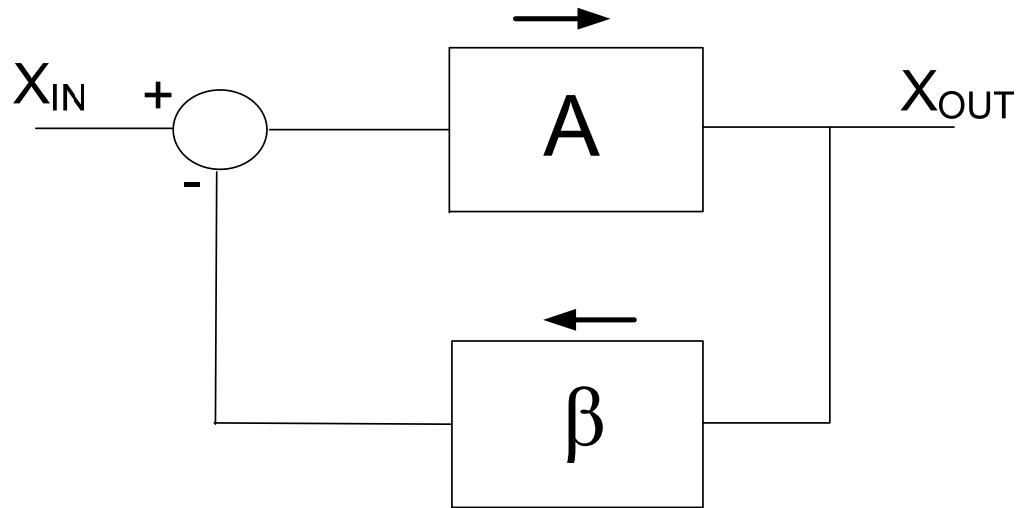
Although not the inventor of feedback, major contributor to the field. Introduced the “Bode Plot” concept, widely used in feedback systems, in 1938 at the age of 33



Hendrik Bode

Grew up in Champaign-Urbana Illinois area,

The feedback concept



$$X_{OUT} = A(X_{IN} - \beta X_{OUT})$$

$$A_{FB} = \frac{A}{1 + A\beta}$$

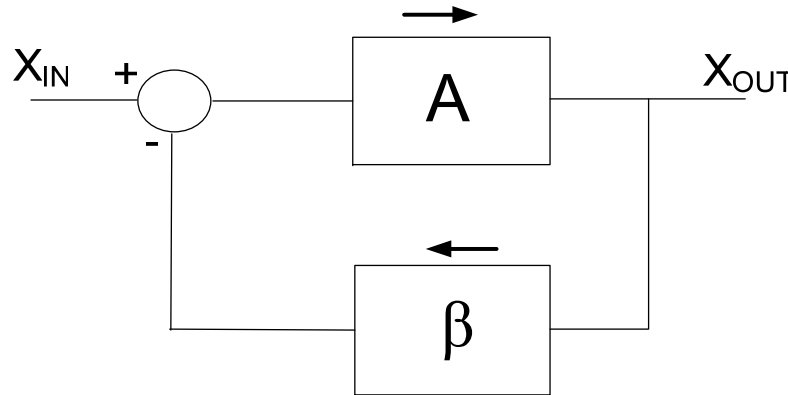
If A is very large so that $A\beta \gg 1$

$$A_{FB} \simeq \frac{1}{\beta}$$

The feedback concept

$$A_{FB} = \frac{A}{1 + A\beta}$$

$$A_{FB} \simeq \frac{1}{\beta}$$



Feedback has shifted the performance requirements from the A amplifier to the β amplifier.

The performance improvements in most things of interest is often improved by a factor of $1+A\beta$ (will show this later)

$D=1+A\beta$ is called the desensitivity

Example: If $A=10^5$ and $\beta=1/2$

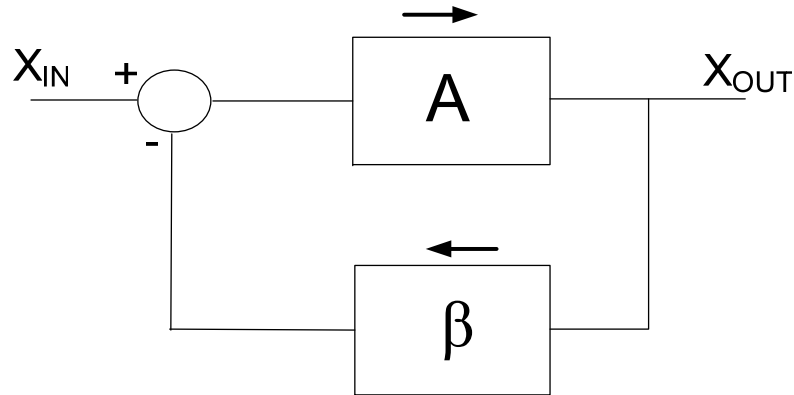
$$A_{FB} \simeq 2$$

$$D=1+50,000 \approx 50,000$$

The feedback concept

$$A_{FB} = \frac{A}{1 + A\beta}$$

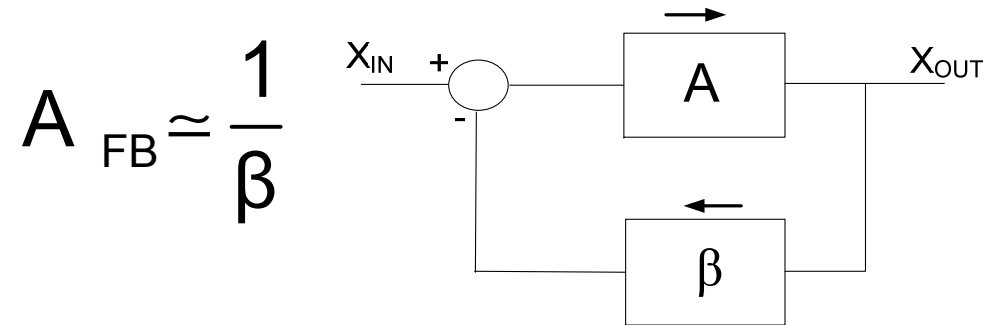
$$A_{FB} \simeq \frac{1}{\beta}$$



Feedback has shifted the performance requirements from the A amplifier to the β amplifier.

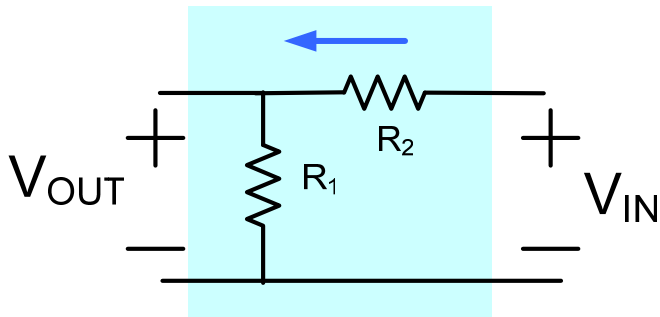
Why is it easier to make a very good β amplifier rather than a very good A amplifier?

The feedback concept



Why is it easier to make a very good β amplifier rather than a very good A amplifier?

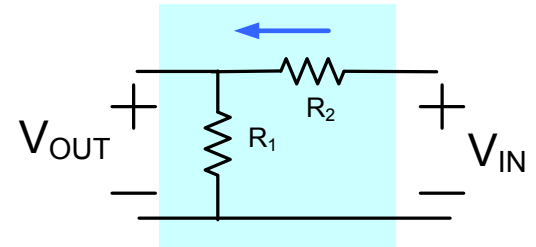
Consider the following β amplifier



$$\beta = \frac{V_{OUT}}{V_{IN}} = \frac{R_1}{R_1 + R_2}$$

- Simply an attenuator
- Very precise control of β practical
- Very linear
- Nearly independent of f
- Very low cost (in discrete form)

The feedback concept



Example: Determine A_{FB} if $\beta = \frac{R_1}{R_1 + R_2}$

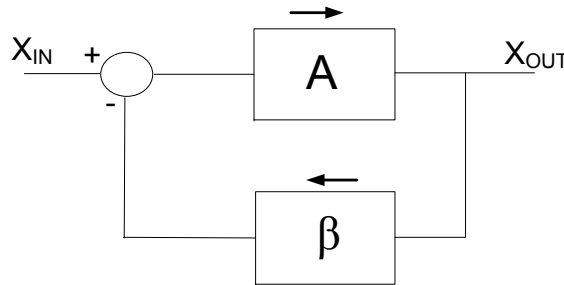
$$A_{FB} \approx \frac{1}{\beta}$$

$$A_{FB} \approx 1 + \frac{R_2}{R_1}$$

If $A_{FB} \approx \frac{1}{\beta}$, what are the effects of A on the performance of the feedback amplifier?

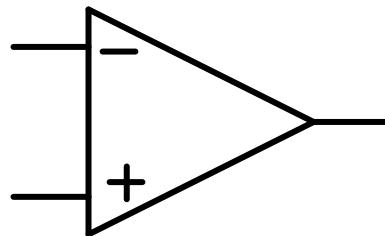
Ideally, the effects of the A amplifier can not be seen at the output!

The feedback concept



Since 1927, the major emphasis on amplifier design has been shifted to building amplifiers with a very large gain

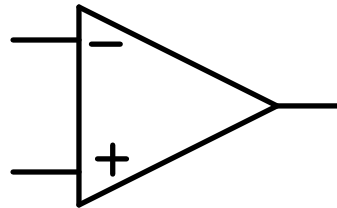
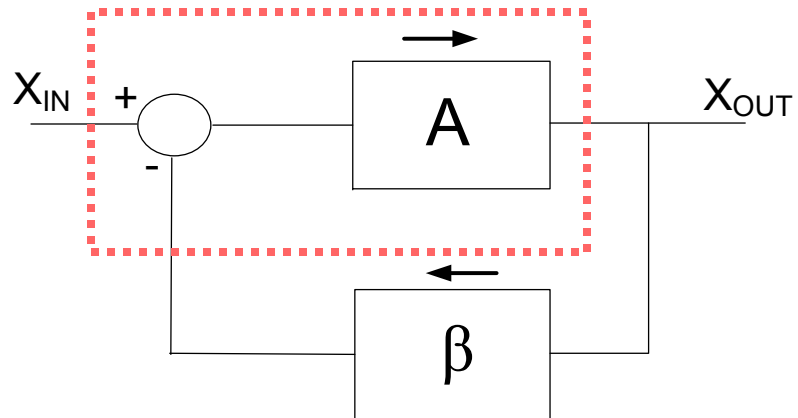
These amplifiers are called Operational Amplifiers (Op Amps)



Op Amp Symbol

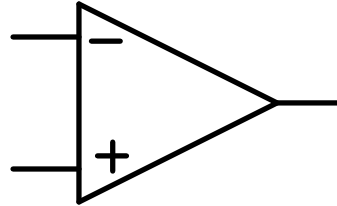
Many useful applications of operational amplifiers have evolved over the years that invariably use feedback but may not be direct extensions of Black's concepts

The feedback concept



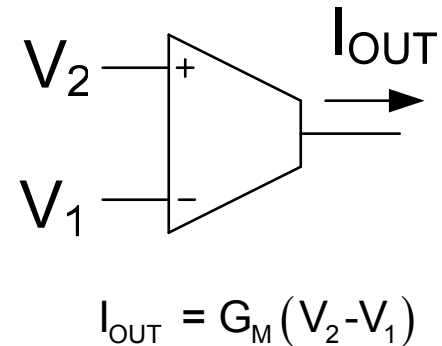
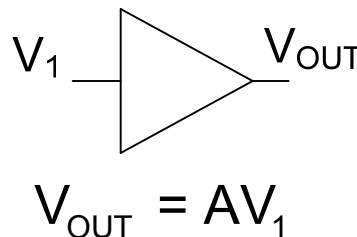
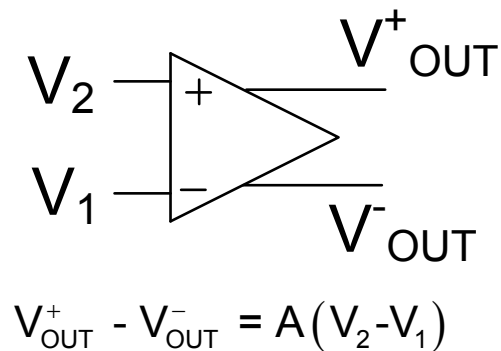
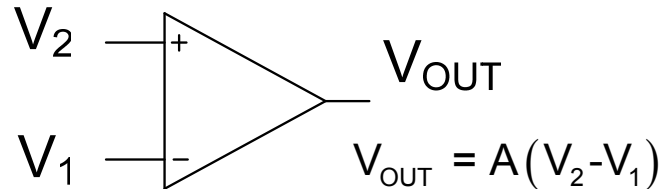
Summer may be combined with amplifier to form a two-input device

The Operational Amplifier

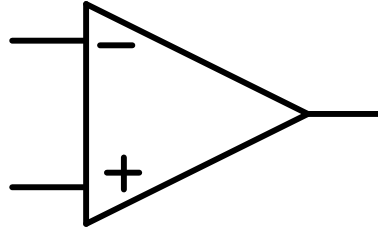


The operational amplifier can be any of the 4 basic types of amplifiers with either one or two inputs and either one or two outputs but always with a large gain

Some possible operational amplifiers



The Operational Amplifier



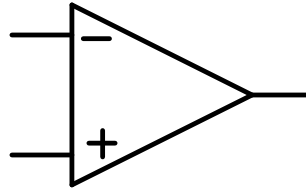
An Op Amp is a very high gain 3-terminal Voltage Amplifier



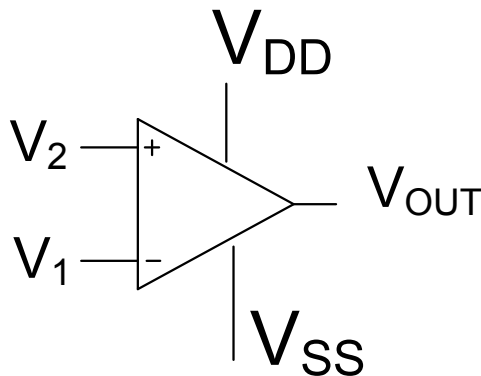
Conventional Wisdom

- Sedra and Smith state that the operational amplifier is always a voltage amplifier with two inputs and a single output
- This is consistent with what is and has been done in almost all electronics texts
- To avoid confusion and inconsistency with the text, we will assume throughout the course that an operational amplifier is ideally a voltage amplifier with two inputs and one output unless otherwise stated

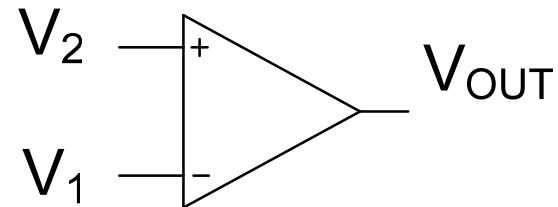
The Operational Amplifier



A source or sources of dc power are needed to power the amplifier
These are called the biasing source or sources

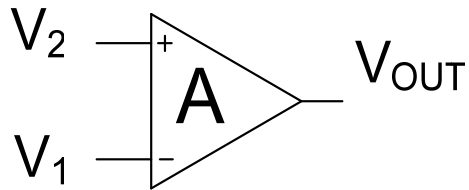


Symbol showing biasing sources



Biasing sources usually not shown but
MUST be present

The Operational Amplifier



$$V_{OUT} = A(V_2 - V_1)$$

Alternate notation $V_2 = V^+$, $V_1 = V^-$

The ideal Op Amp

$$A \approx \infty$$

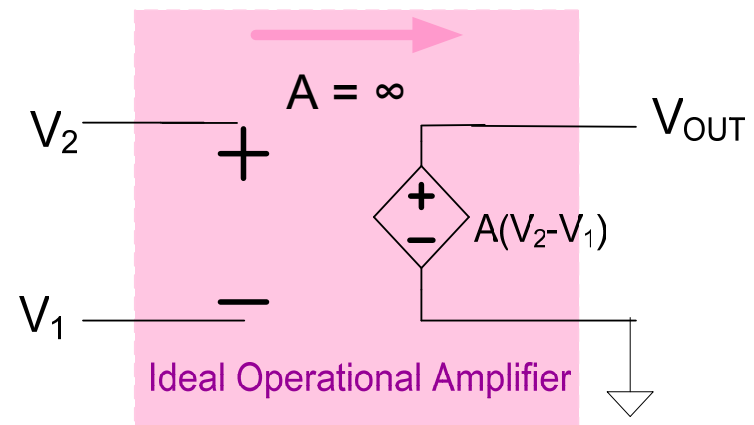
$$R_{IN} = \infty$$

$$R_{OUT} = 0$$

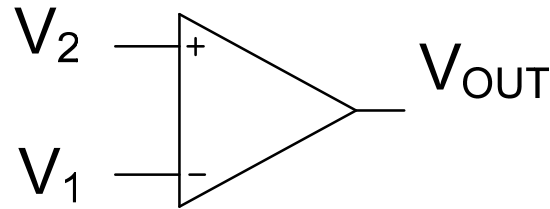
$$V^+ = V^-$$

“E” source model in SPICE or SPECTRE
can be used to model the Op Amp

Just make A large (maybe 10^8) to model ideal op amp

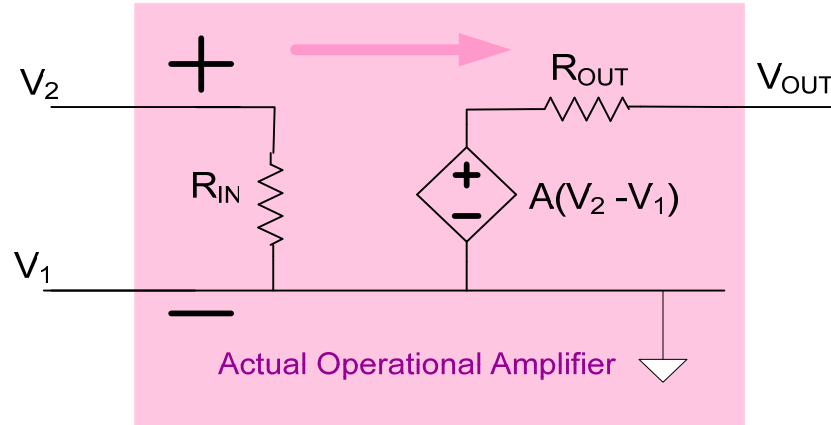


The Operational Amplifier



The actual Op Amp

Many different products (1000's) with a wide variety of specifications



Typical for catalog parts:

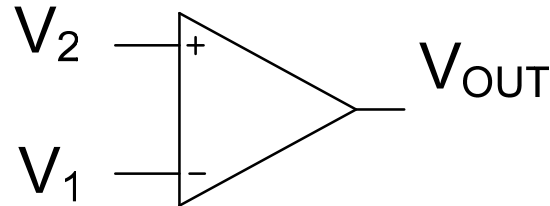
$$A \sim 10^5 \text{ to } 10^6$$

$$R_{OUT} \sim 50\Omega \text{ to } 100\Omega$$

$$R_{IN} \sim \begin{cases} 1M\Omega & \text{bipolar OpAmps} \\ >100M\Omega & \text{FET input OpAmps} \end{cases}$$

The Operational Amplifier

Op Amp Models



Several different models of the op amp will be introduced throughout the course

The ideal model is adequate in many applications



Invariably, if a nonideal op amp model is necessary to adequately predict the performance of a feedback circuit, then the feedback circuit is likely not very practical

But, often the use of a more accurate model is needed to ascertain the simpler ideal model is adequate



End of Lecture 9