Section 1
Introduction to Analog and Digital Electronics

Sedra/Smith, Sections 1.4- 1.7

Outline of Section 1

1.1 Analog Amplifiers

- Linear Amplifiers
- Transfer Characteristic
- Operating point
- Classification of ideal amplifier topologies and desirable properties
- Input/Output resistance
- Cascaded amplifier stages

1.2 Frequency Response of Amplifiers

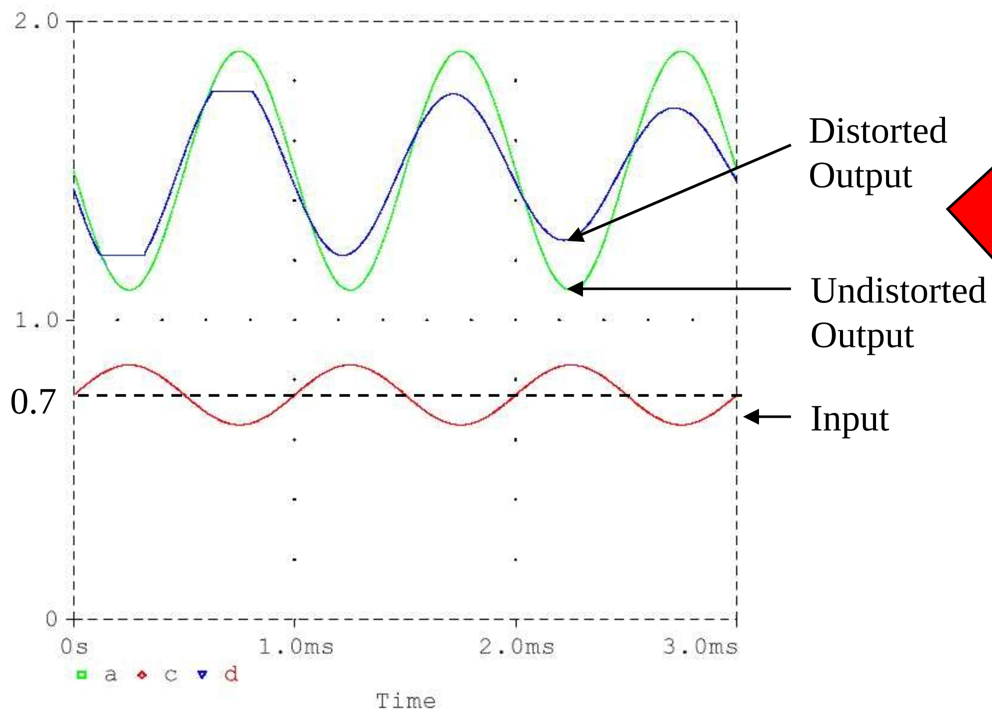
1.3 Digital Logic Inverters

Linear Amplifiers (1)

- Multiply amplitude of a signal by a constant scalar quantity

  i.e. $x_o(t) = A \cdot x_i(t)$

- Non-scalar or non-uniform amplification is called **distortion**



- Only the signal portion of the input is amplified by the amplifier
- DC component may be shifted up or down

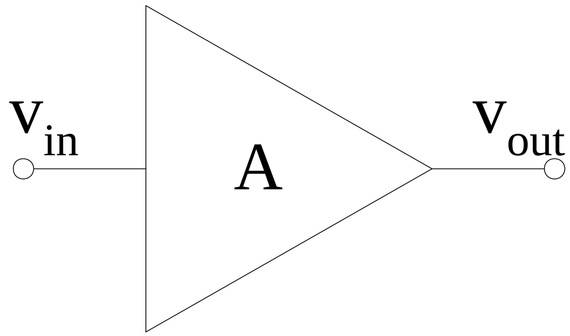
Linear Amplifiers (2)

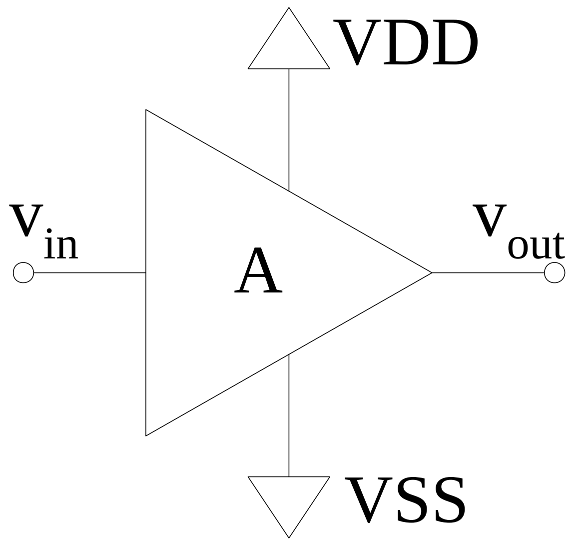
- Symbol for a single-ended input linear voltage amplifier:
- Ideally provides linear voltage gain regardless of the amplitude of the input signal

- Real amplifiers have power supplies that limit the amplitude of the output

  i.e. $\left|v_{out_{MAX}}(t)\right| \leq VDD - VSS$

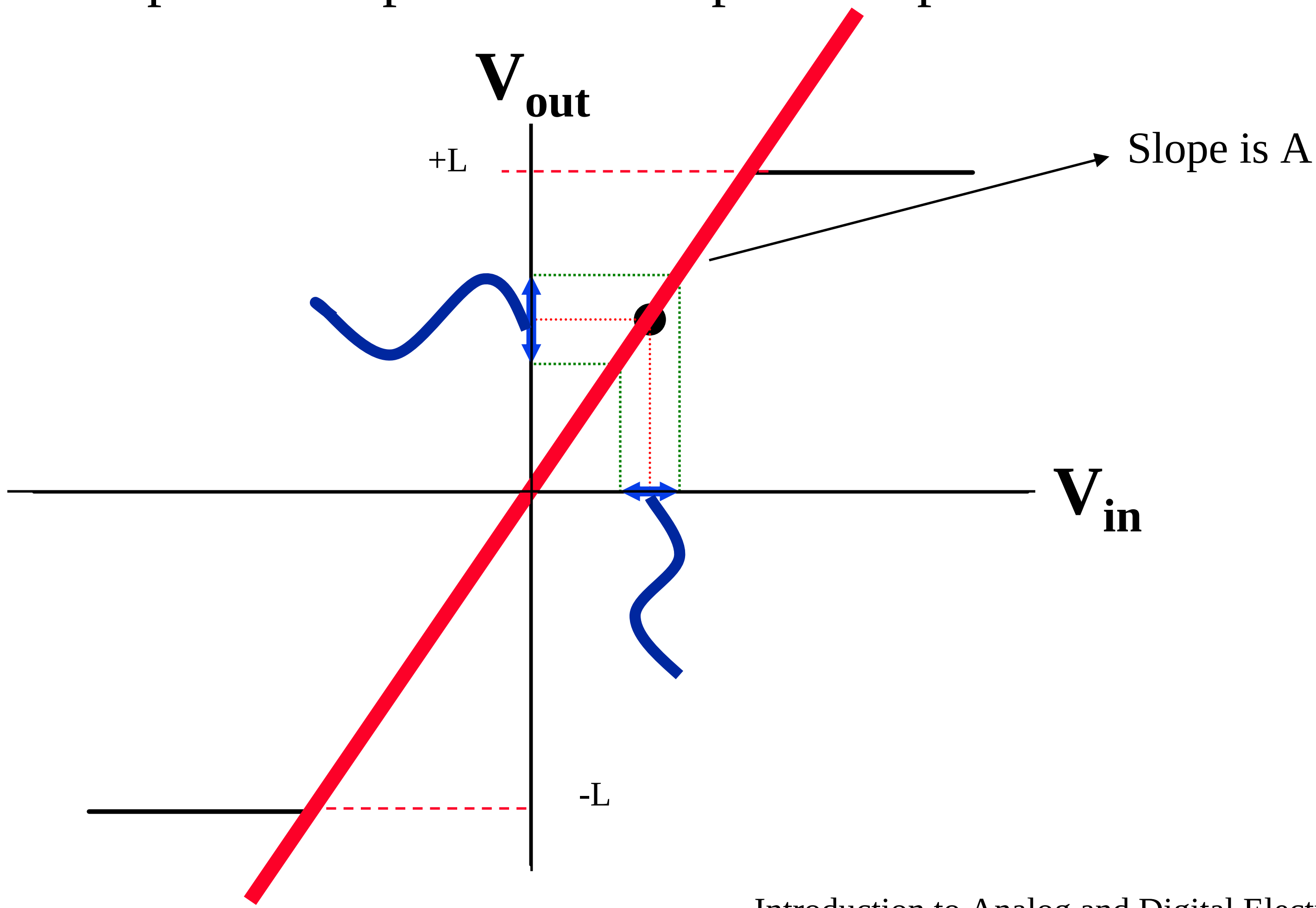
- If input is too large, output clamps ⇨ **gain saturation**





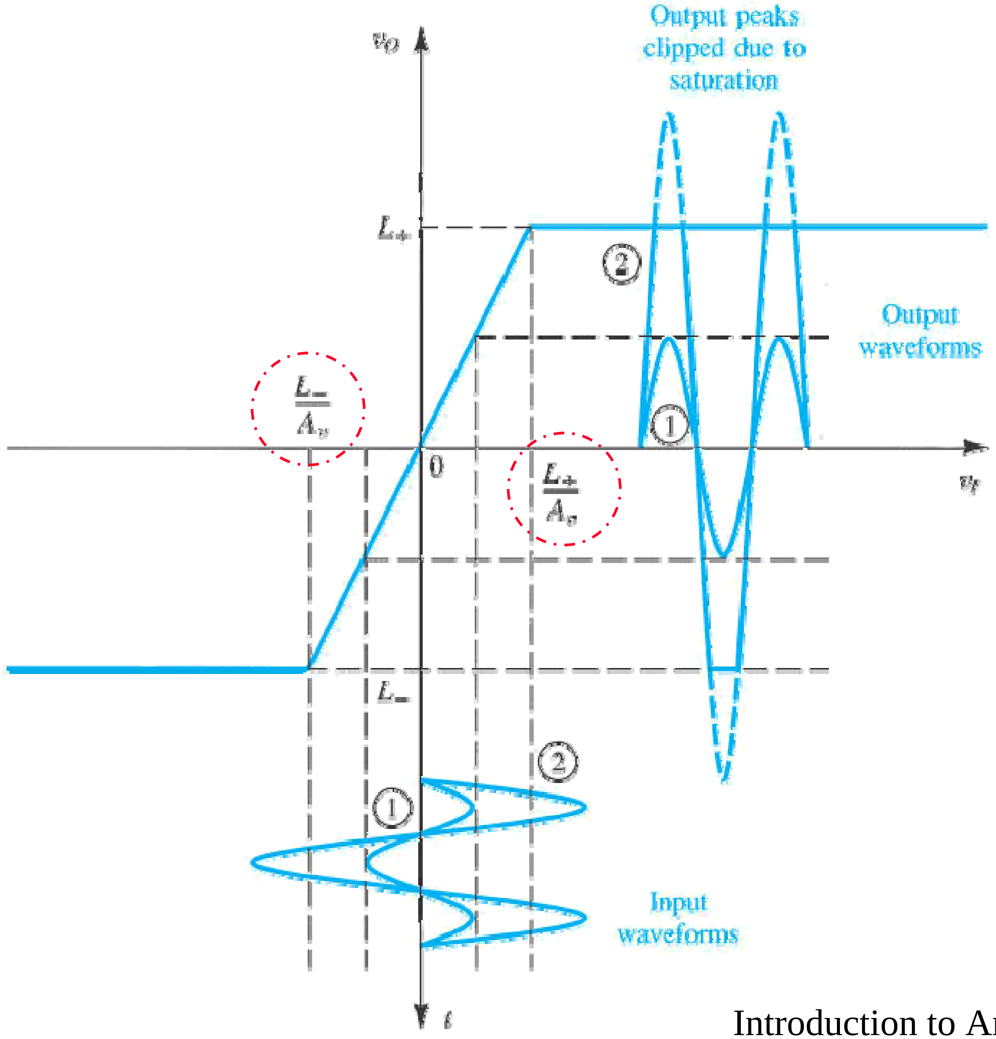
Transfer Characteristic(1)

- Plot of amplifier output versus amplifier input

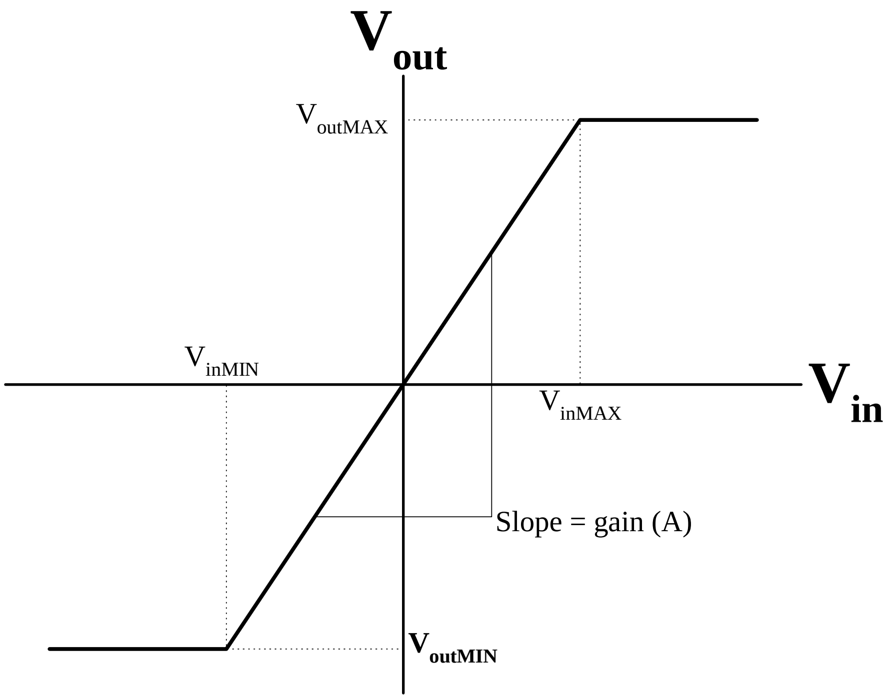


Transfer Characteristic

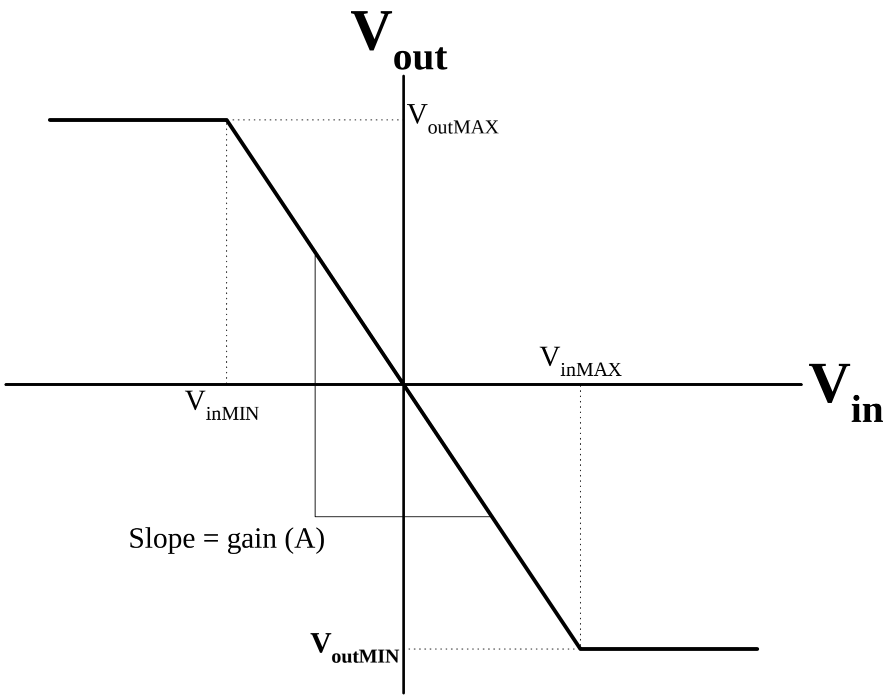
- Fig 1.13 Text book: Amplifier Saturation



Transfer Characteristic (2)



Amplifier with positive gain

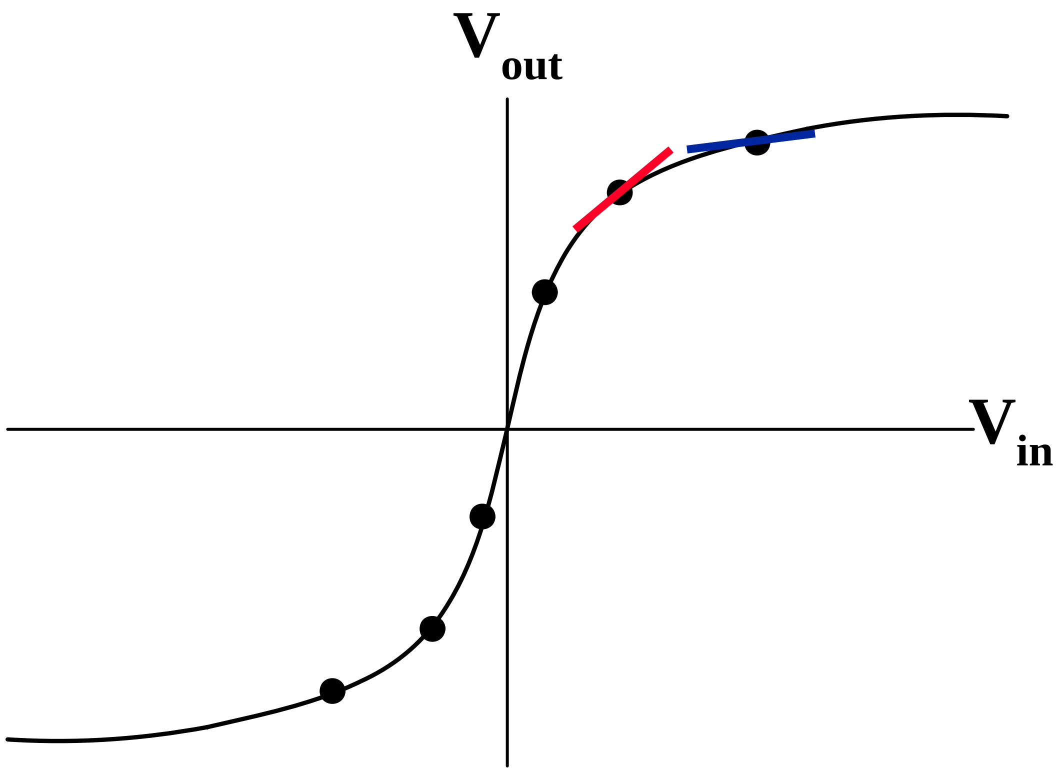


Amplifier with negative gain

- To operate amplifier in its linear region, the input must be kept small enough

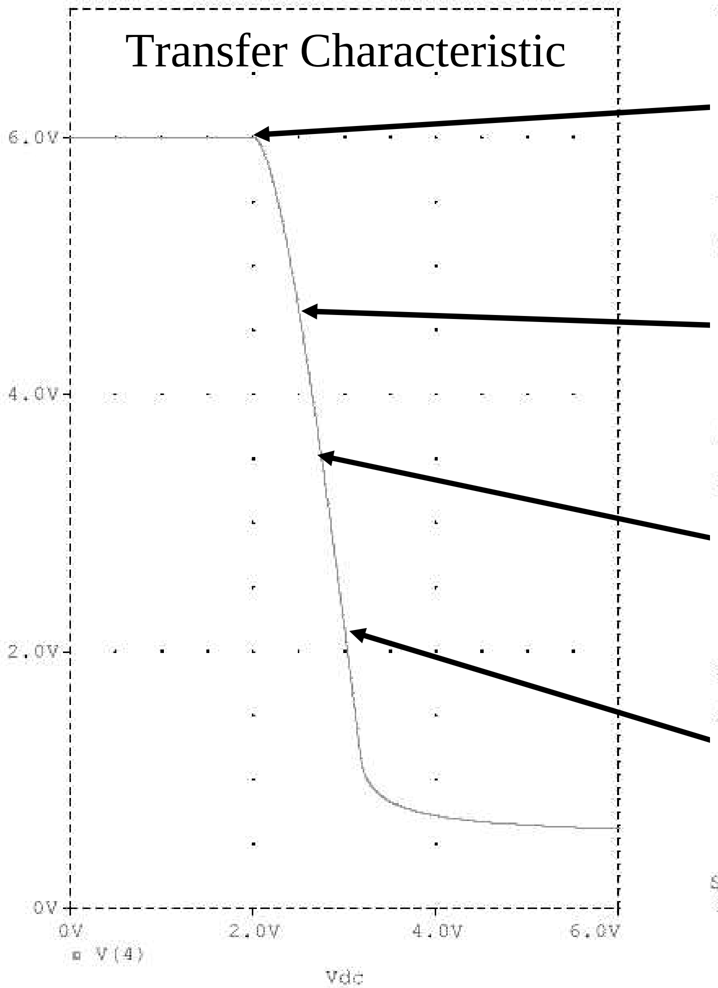
Operating Point (1)

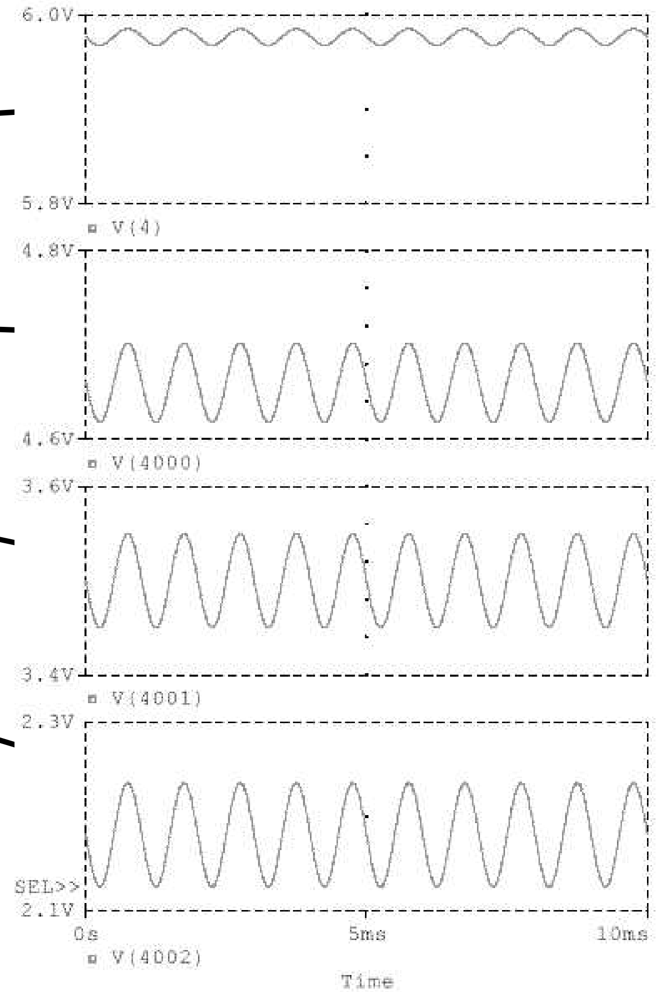
- Realistic transfer characteristic:



- Each circle represents a different DC component for the input and output signals
  - called an **operating point**
- Location of operating point has an effect on
  - input signal range
  - amplifier gain magnitude
  - amount of distortion

Operating Point (2)





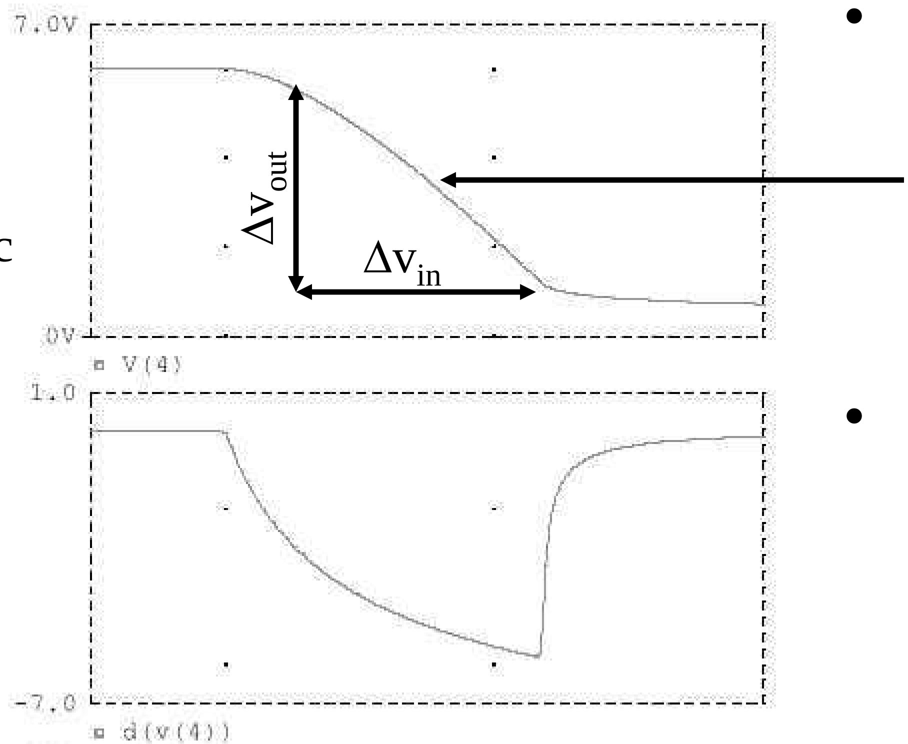
Amplifier Output

- Note how operating point affects:
  - voltage gain
  - output DC voltage
  - allowable input magnitude range

Operating Point (3)

Transfer Characteristic

First Derivative



- Input and output signal amplitude ranges maximized when operating point is near middle of linear region
- Derivative of transfer characteristic gives measure of amplifier gain linearity (and distortion)

Signal Convention for Course

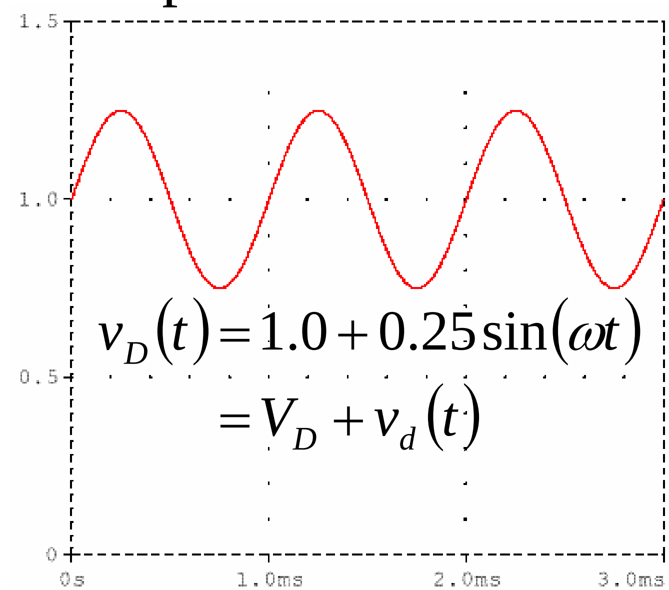
- ***DC*** magnitudes in uppercase symbol and subscript
  - Example: I_D, V_D
- Incremental ***signal*** quantities in lowercase symbol & subscript
  - Example: $i_d(t)$, $v_d(t)$
- Total ***DC + signal*** quantities in lowercase symbol, uppercase subscript
  - Example: $i_D(t)$, $v_D(t)$

In general:

$$i_D(t) = I_D + i_d(t)$$

$$v_D(t) = V_D + v_d(t)$$

Example:



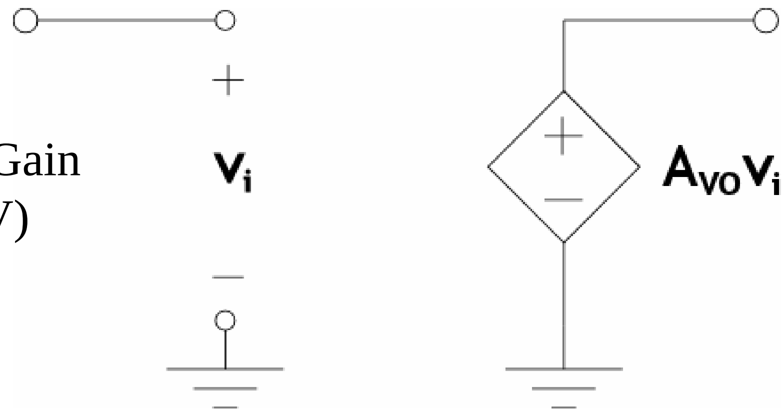
Amplifier Classification

- Four types:

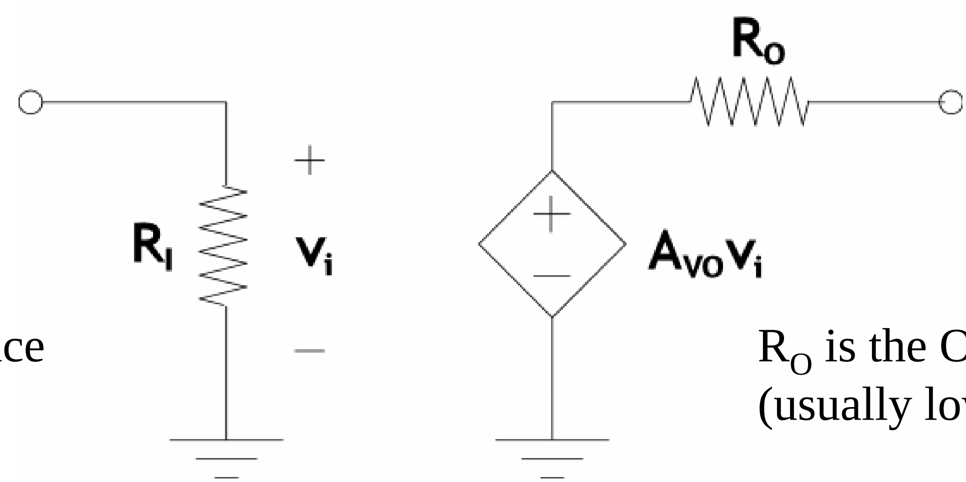
	Input	**Output**
Voltage	Voltage	Voltage
Current	Current	Current
Transconductance	Voltage	Current
Transresistance	Current	Voltage

Ideal Voltage Amplifier

A_{VO} is the open-circuit Gain
(usually large 1,000 V/V)



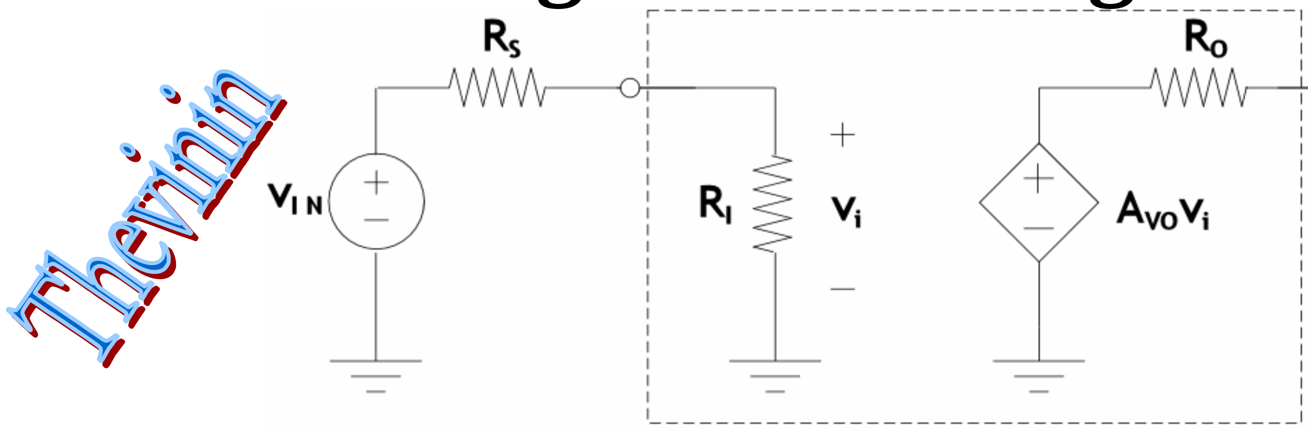
"Real" Voltage Amplifier



R_I is the Input Resistance
(usually large 100 kΩ)

R_O is the Output Resistance
(usually low 100 Ω)

Loading of the Voltage Amplifier



$$A_{V2} = \frac{v_i}{v_{IN}} = \frac{R_i}{R_i + R_S}$$

$$A_{V1} = \frac{v_{out}}{v_i} = \frac{R_L}{R_L + R_O}(A_{VO})$$

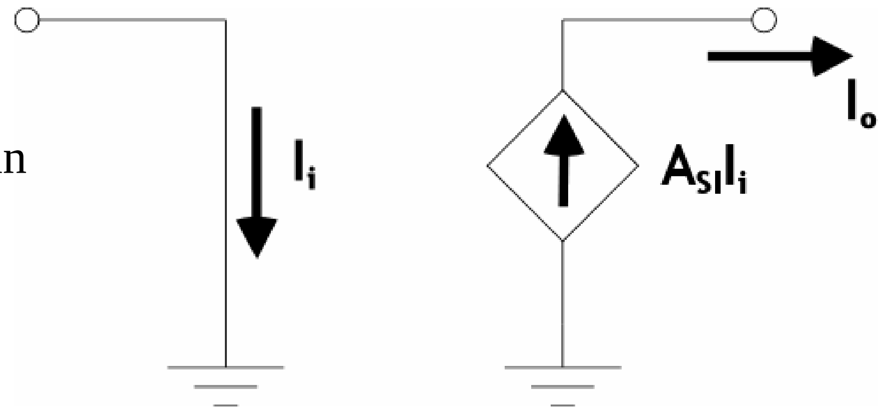
$$A_V = \frac{v_{out}}{v_i} \cdot \frac{v_i}{v_{IN}} = \frac{R_i}{R_i + R_S} \cdot \frac{R_L}{R_L + R_O}(A_{VO})$$

- $A_V < A_{VO}$ due to two voltage divisions (at source and load)

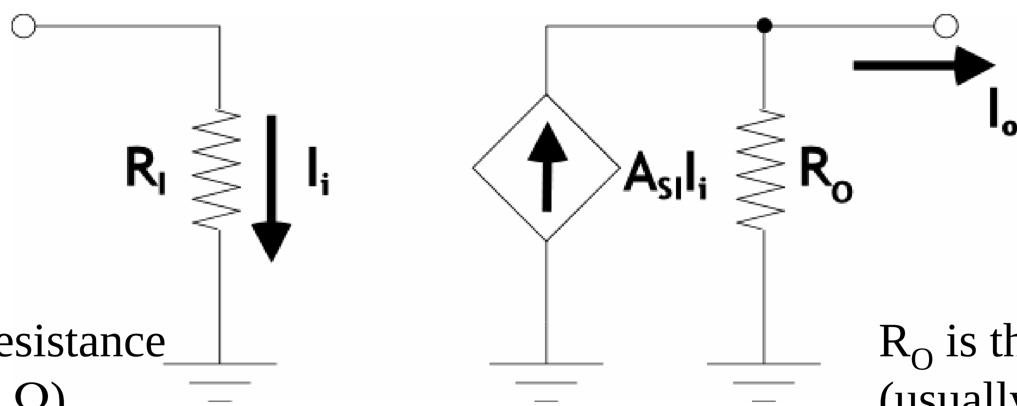
A_V maximized with large R_{IN} (R_I), and small R_{OUT} (R_O)

Ideal Current Amplifier

A_{SI} is the open-loop Gain
(usually large 100 A/A)



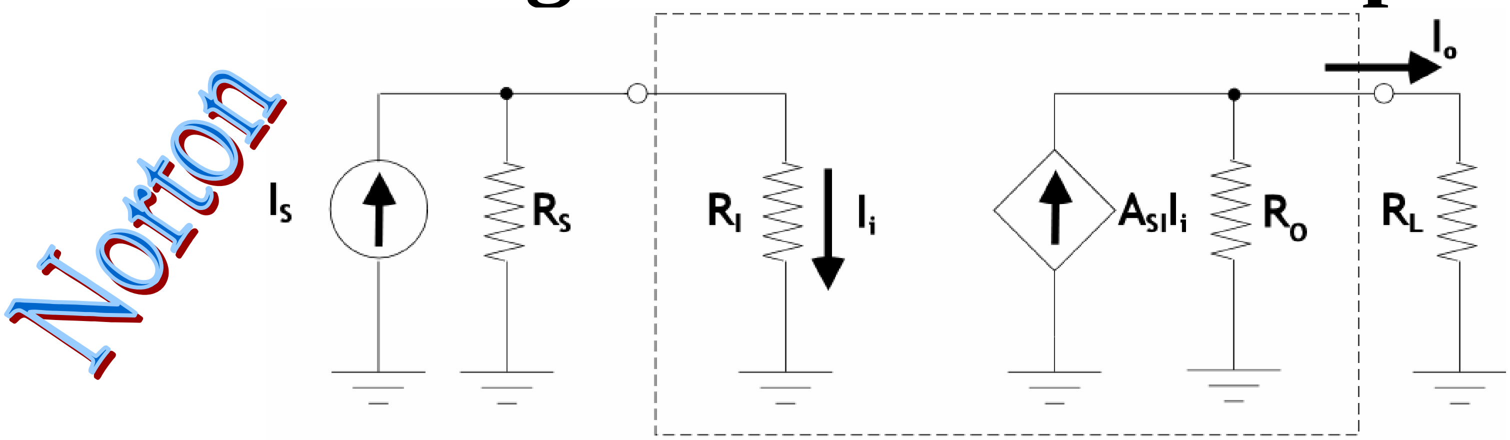
"Real" Current Amplifier



R_I is the Input Resistance
(usually low 100 Ω)

R_O is the Output Resistance
(usually high 100 kΩ)

Loading of the Current Amplifier



$$A_{I2} = \frac{I_i}{I_S} = \frac{R_S}{R_S + R_i}$$

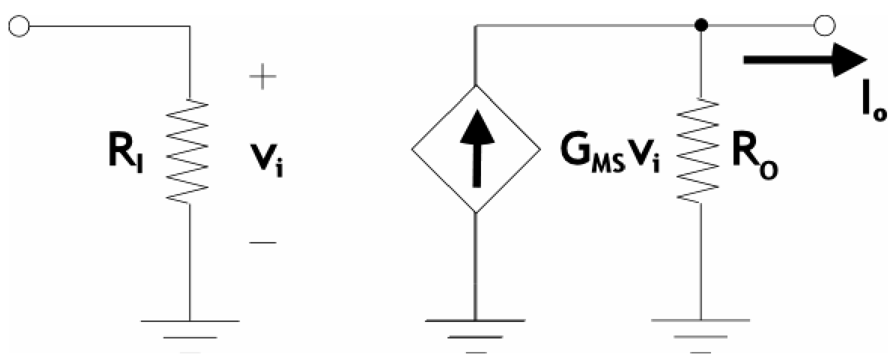
$$A_{I1} = \frac{I_O}{I_i} = \frac{R_O}{R_O + R_L}(A_{IS})$$

$$A_I = \frac{I_O}{I_i} \cdot \frac{I_i}{I_S} = \frac{R_S}{R_S + R_i} \cdot \frac{R_O}{R_O + R_L}(A_{IS})$$

- $A_I < A_{IS}$ due to two current divisions (at source and load)

A_I maximized with small R_{IN} (R_I), large R_{OUT} (R_O)

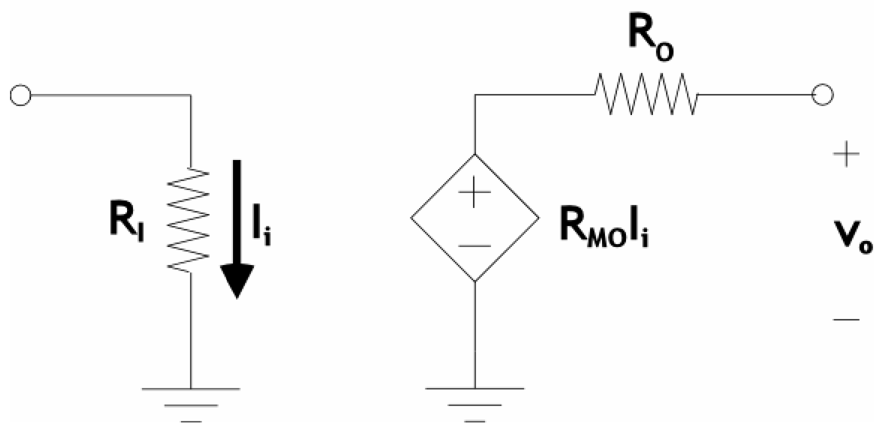
Transconductance Amplifier



- **G_{MS}** is the short-circuit transconductance
- Usually:

R_{IN} is large and R_{OUT} is large

Transresistance Amplifier



- **R_{MO}** is the open-circuit transresistance gain
- Usually:

R_{IN} is small and R_{OUT} is small

Photodetectors !

2-port Network

- So far the amplifier we discussed look like two port devices
- Tow port devices can be described by two port network elements such as *z* parameters, *y* parameters, *h* (hybrid parameters) and *g* (Inverse hybrid parameters)
- In EC1, we don't study the details of working with two port network parameters. Read Appendix B of your text book for more information about two port network parameters
- These parameters include a component showing reverse transmission of the signal from output to input

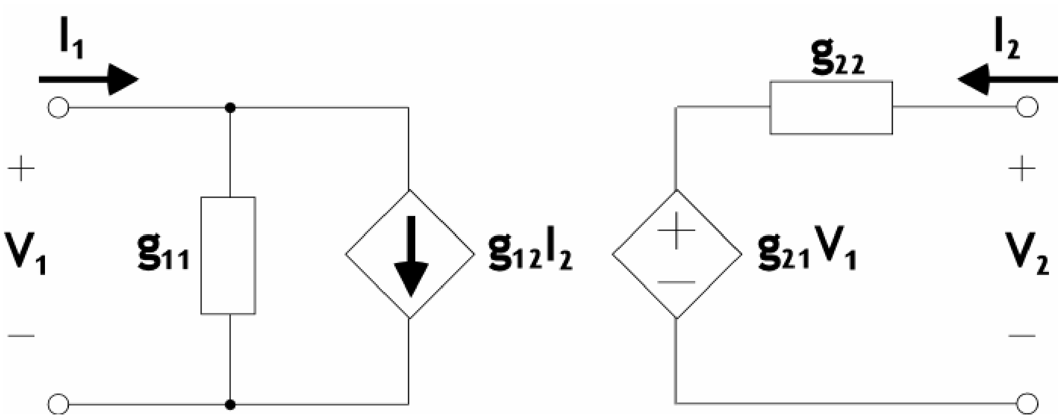
$$V_1 = z_{11} I_1 + z_{12} I_2$$
$$V_2 = z_{21} I_1 + z_{22} I_2$$

$$I_1 = y_{11} V_1 + y_{12} V_2$$
$$I_2 = y_{21} V_1 + y_{22} V_2$$

2-port Network (g-parameter)

- Real Amplifiers must also contain a Reverse-Transmission component !
- For example, a 2-port network using g-parameters

$$I_1 = g_{11}V_1 + g_{12}I_2$$
$$V_2 = g_{21}V_1 + g_{22}I_2$$

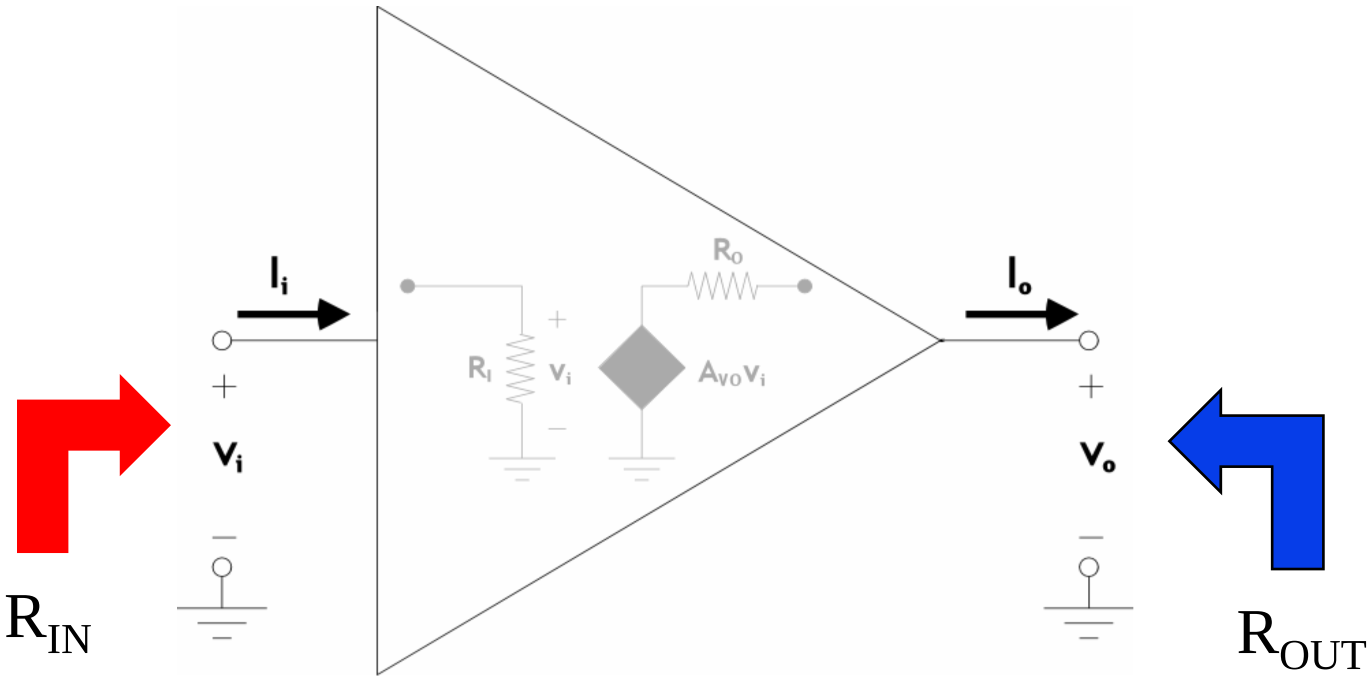


- g_{11}: input admittance
- g_{12}: reverse current gain
- g_{21}: forward voltage gain
- g_{22}: output impedance

Reverse transmission assumed negligible in EC1

Input and Output Resistance

- Methods needed to determine R_{IN} and R_{OUT} for a given black-box amplifier

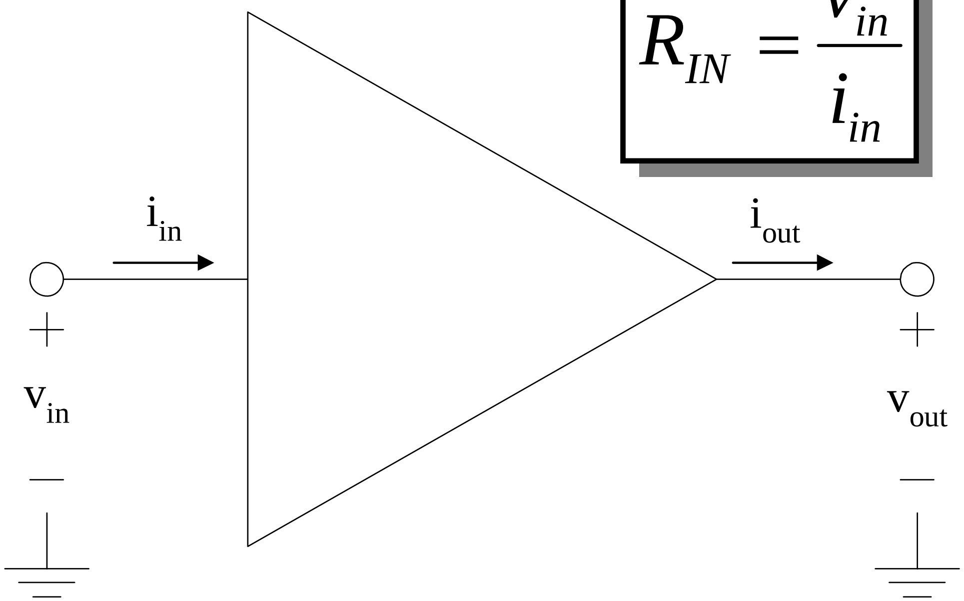


Finding R_{IN}

- R_{IN} is the resistance "seen" between the input node and ground
- With input signal applied, v_{in} and i_{in} signals are established

$$R_{IN} = \frac{v_{in}}{i_{in}}$$

- Result is independent of amplifier class



Important:
R_{IN} can usually be obtained by inspection

Finding R_{OUT} - Method 1

- With input signal applied, v_{out} and i_{out} signals are established and are dependent on attached load resistance

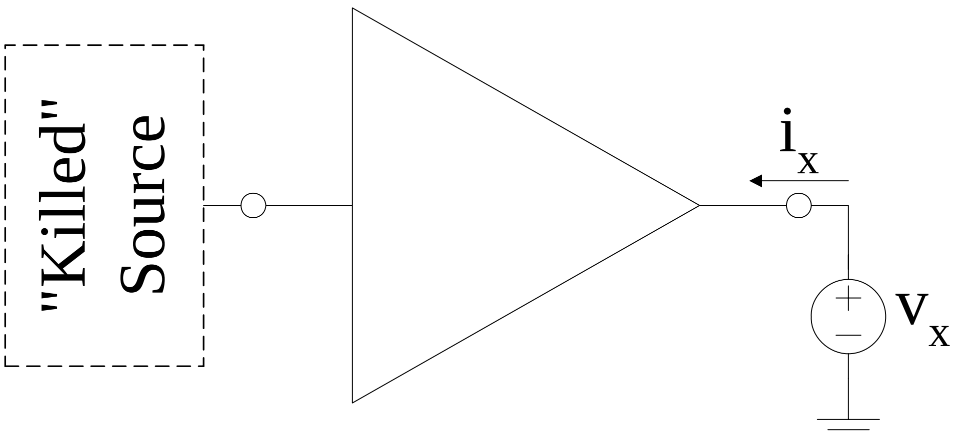
- To get R_{OUT} for a given input:
  - remove load (open-circuit the output), determine v_{out}
  - short load (short-circuit the output), determine i_{out}

$$R_{OUT} = \frac{v_{out}\big|_{open-circuit}}{i_{out}\big|_{short-circuit}}$$

- Result is independent of amplifier class and input signal

Finding R_{OUT} - Method 2

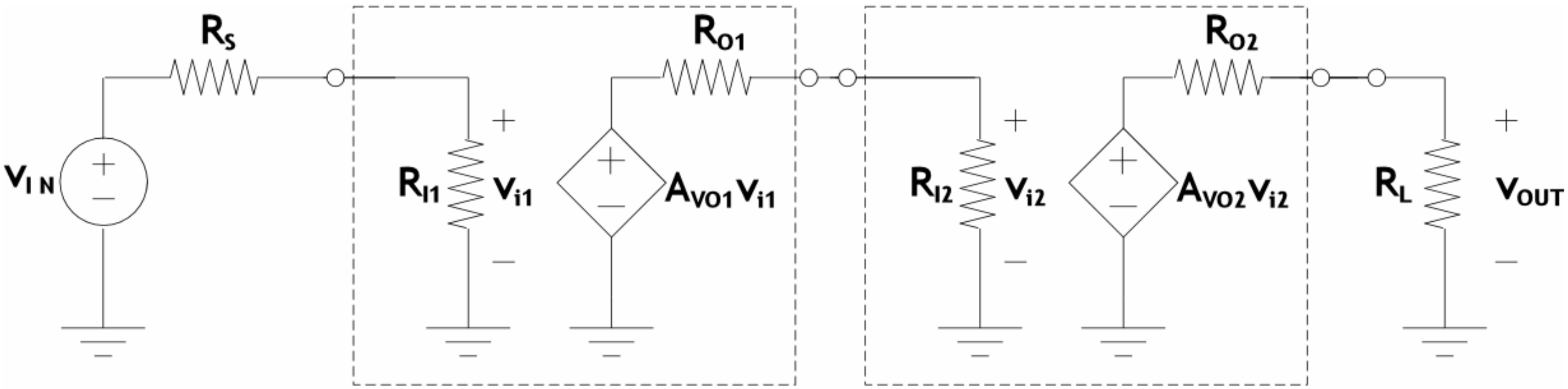
- Alternatively, one can determine R_{OUT} as follows:
  - "Kill" the input signal (set v_{in} or i_{in} to zero)
  - Apply a test voltage signal v_x to the output node
  - Determine the current i_x it supplies to the circuit



$$R_{OUT} = \frac{v_x}{i_x}$$

- Result is independent of amplifier class (Norton's Theorem)

Cascaded Amplifier Stages

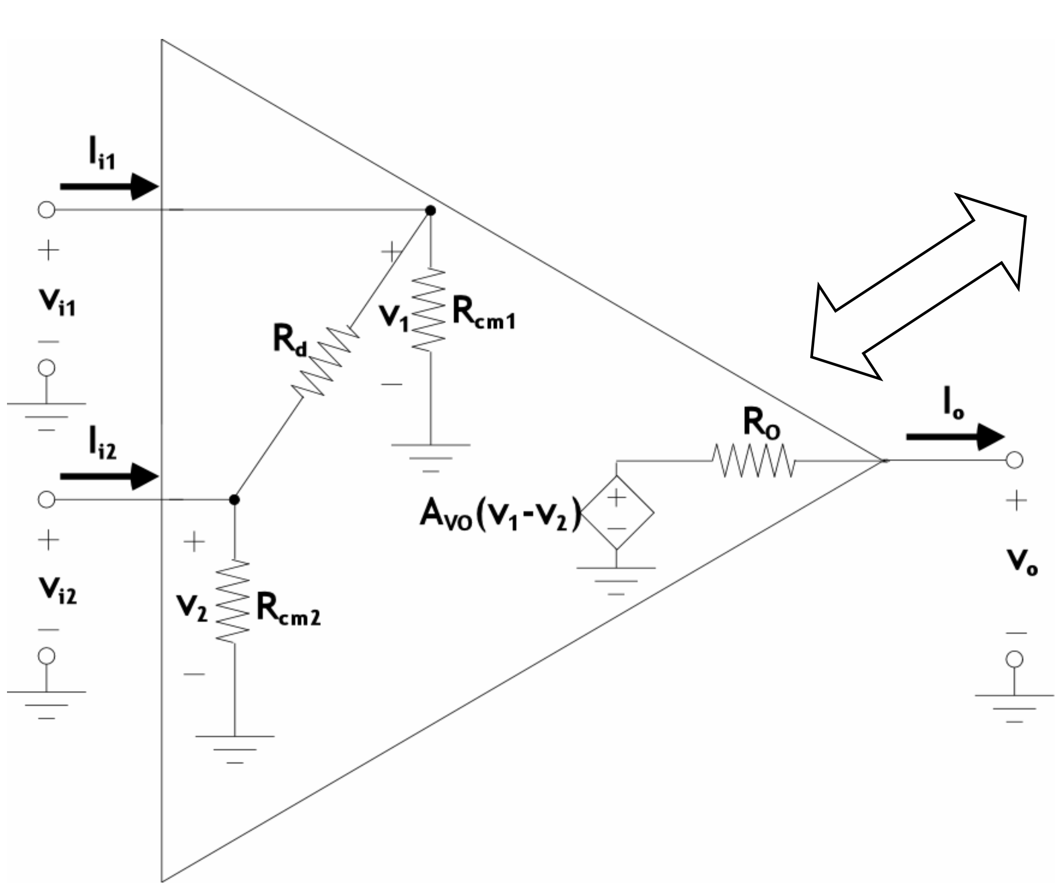


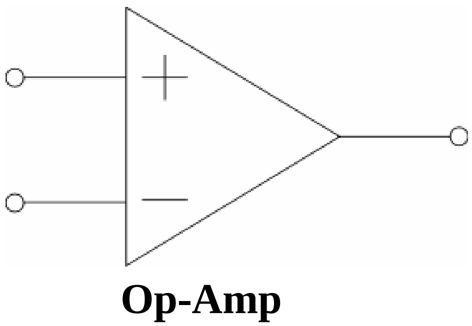
- Determine the relevant parameters (gain, R_{IN}, R_{OUT}) of each stage
- Overall gain analysis then becomes trivial (voltage & current dividers)

Then, by inspection…

$$A_V = \frac{v_{out}}{v_{IN}} = \frac{R_L}{R_L + R_{O2}} \cdot A_{VO2} \cdot \frac{R_{i2}}{R_{i2} + R_{O1}} \cdot A_{VO1} \cdot \frac{R_{i1}}{R_{i1} + R_S}$$

Inside the Op-Amp





- The internal circuitry of the “Op-Amp” (or at least a version of it) will be explored by the end of EC1…

1.1 Analog Amplifiers - Summary

- Linear signal amplification and distortion
- Transfer characteristics: input and output range, gain saturation
- Effect of operating point on gain, input and output range
- Classification of ideal amplifiers
- Loading effects and ideal amplifier properties
- How to find the input and output resistance of an amplifier
- Analysis of cascaded amplifier stages

Outline of Section 1.2

1.1 Analog Amplifiers

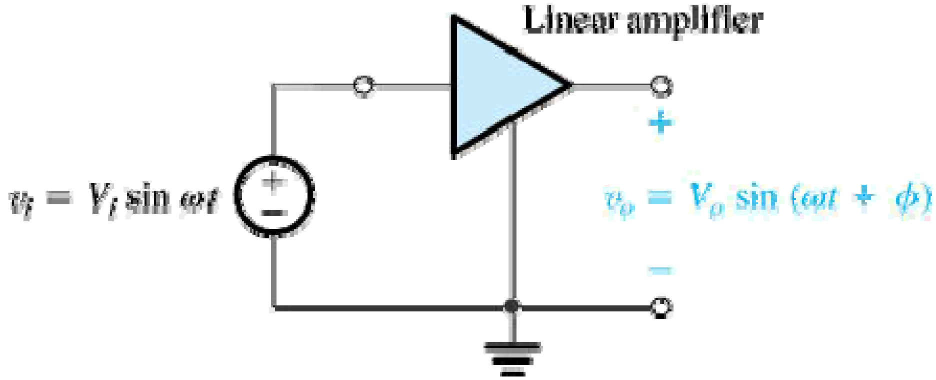
1.2 Frequency Response of Amplifiers

- Measuring the response
- Classification of Amplifiers based on frequency response

1.3 Digital Logic Inverters

Measuring Frequency Response

- When a sine wave signal is applied to a linear circuit the output is a sine wave at the same frequency
- The output can have a different magnitude and experience a phase shift



- Ratio of V_o to V_i is the amplifier gain at the test frequency
- The Transfer function of an amplifier is: ***T(ω)***

$$T(\omega) = \frac{V_o(\omega)}{V_i(\omega)}$$

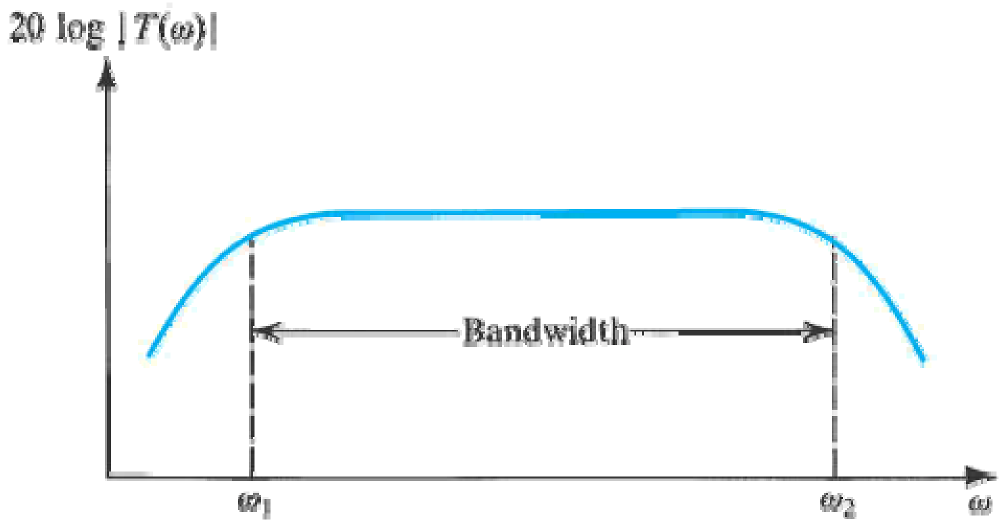
Measuring Frequency Response

- The **frequency response** of an amplifier is completely known by the **magnitude (or amplitude) response** and **phase response**

$$|T(\omega)| = \frac{V_o}{V_i}$$

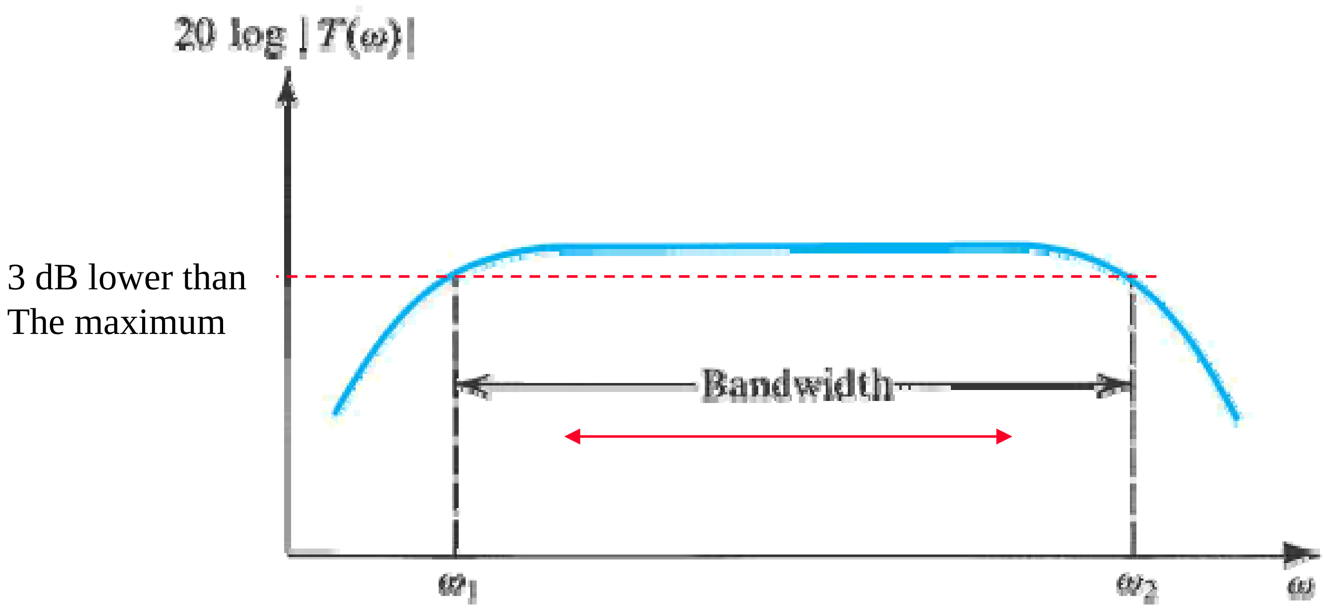
$$\angle T(\omega) = \phi$$

- Often the magnitude plot is given in decibels and **20log|*T(ω)*|** is plotted versus frequency



Frequency Response

- **Amplifier Bandwidth:** The frequency range in which gain is almost constant and doesn't decrease more than (usually) 3 dB



Derivation of Frequency Response

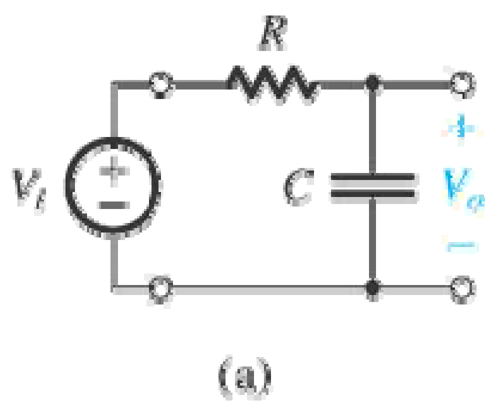
- Find the amplifier equivalent circuit including the reactive components
- L has the impedance of jωL and C has the impedance of 1/jCω
- In many cases complex frequency variable of s is used instead of ω, → sL and 1/sC

$$T(s) = \frac{V_o(s)}{V_i(s)}$$

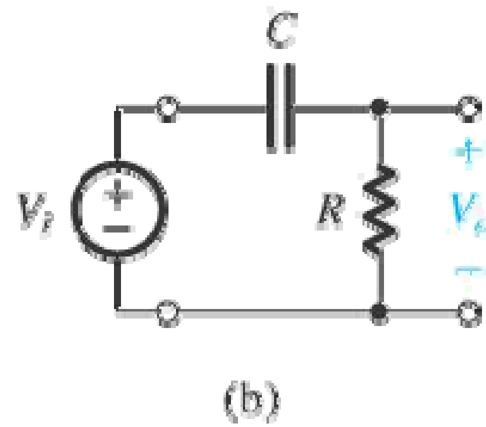
- Replacing s by jω gives the response for physical frequencies: $T(j\omega)=T(\omega)$

Single-Time-Constant Networks

- Circuits with one reactive component (L or C) and one resistance
- Time constant of an STC network: $\tau = L/R$ or $\tau = CR$
- STC networks can be low-pass (LP) or high-pass (HP)



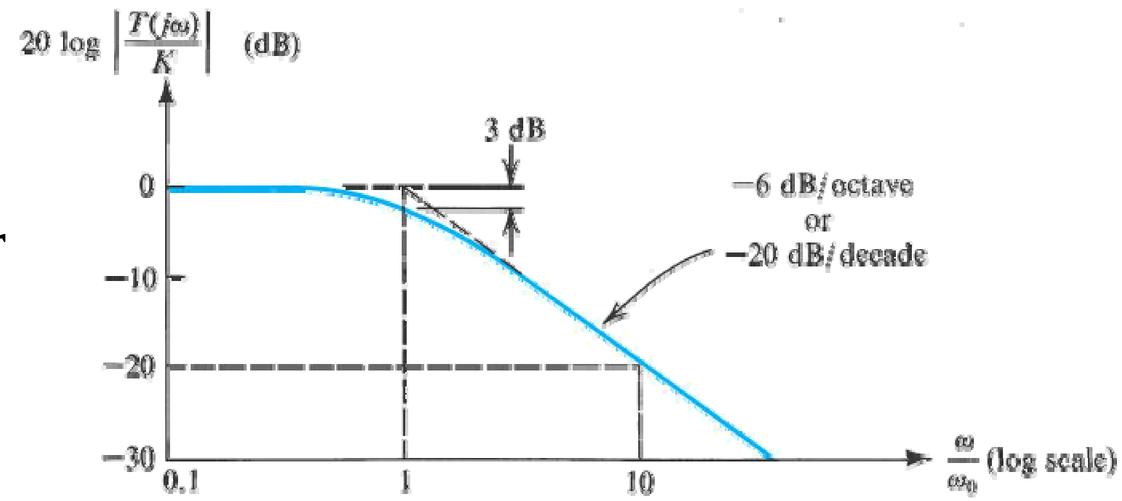
Low-Pass Network



High-Pass Network

STC Network-Bode Plots

- Low-pass STC
- Log scale axis
- 3 dB frequency or Corner frequency



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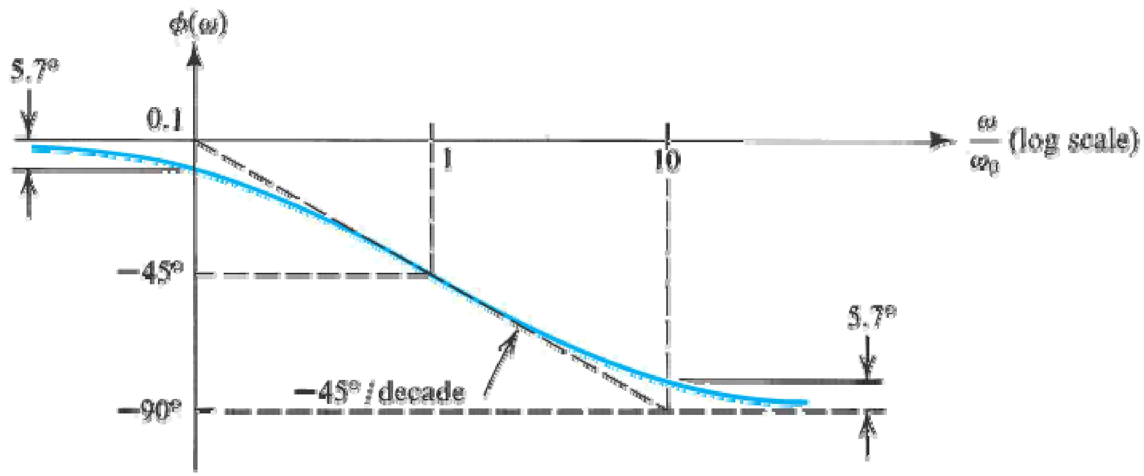
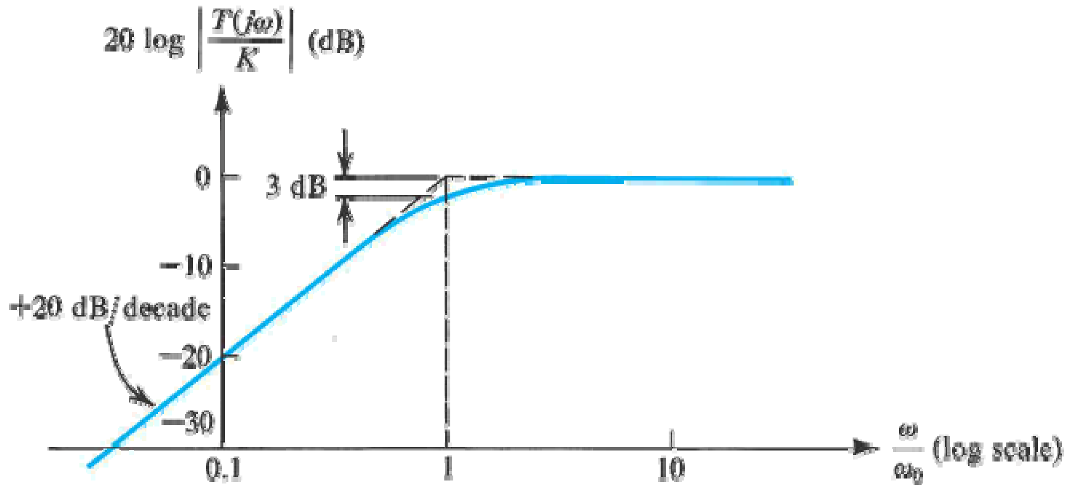


(b)

STC Network-Bode Plots

- High-pass STC
- Log scale axis
- 3 dB frequency or
  Corner frequency



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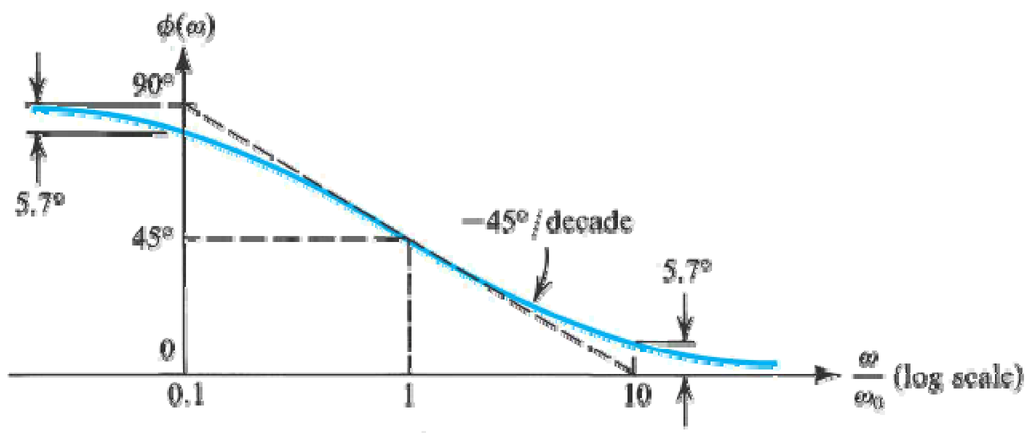
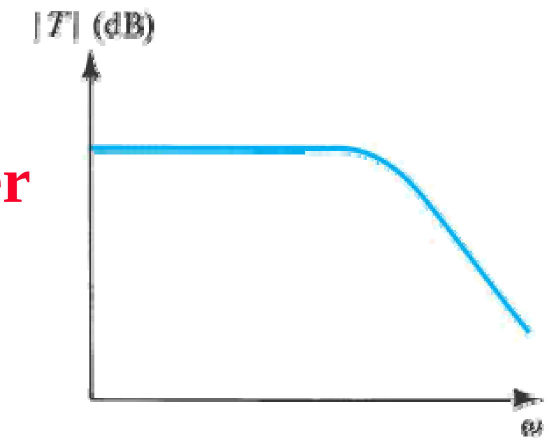


(b)

Another Classification of Amplifiers

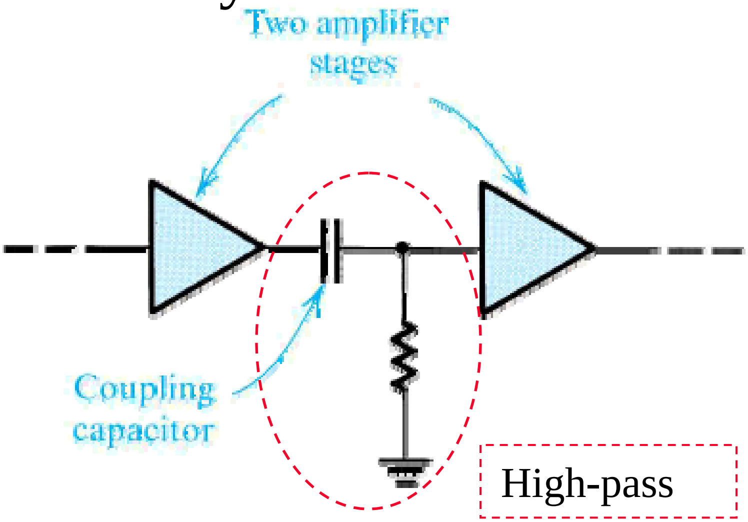
- Base on the shape of the magnitude-response of the amplifiers
- The internal device capacitances and external circuit capacitances cause a limited frequency range and the roll off in the frequency response

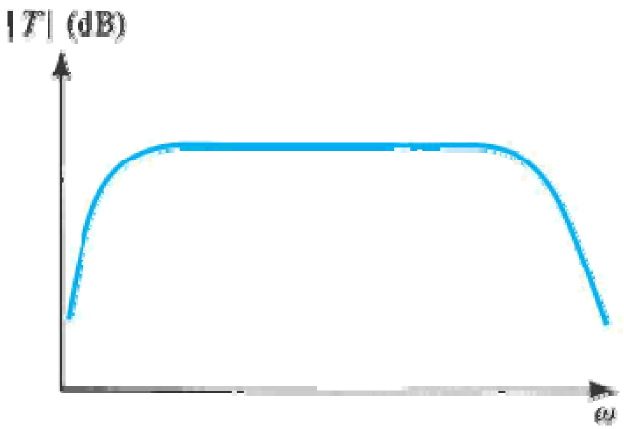
A direct-coupled amplifier or dc amplifier



Another Classification of Amplifiers

- Coupling capacitors are used to connect one amplifier stage to another (few μF)
  - At low frequencies the stages are decoupled as the impedance of the capacitor (1/jCω) is very large
  - Resulting in zero gain at DC
  - They are not used in ICs

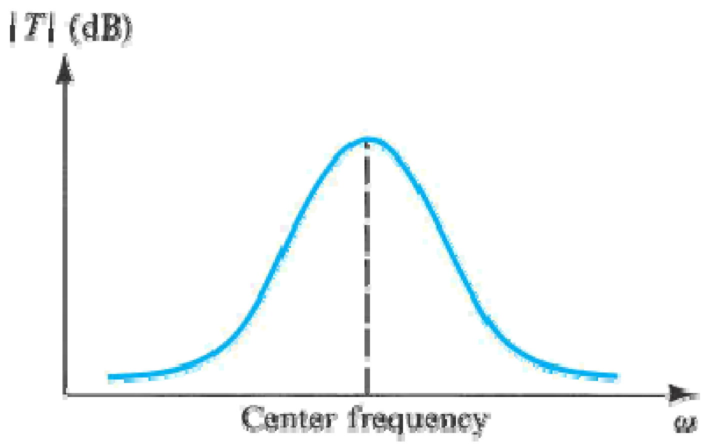




A a capacitively-coupled amplifier or an ac amplifier

Another Classification of Amplifiers

- **A Tuned Amplifier** or **bandpass amplifier** or bandpass filter has a frequency response in which gain peaks around a *center frequency*
- They exist in many electronic systems such as radios, television receivers, front-end of telecommunication receivers



1.2 Frequency Response - Summary

- Transfer function or frequency response of an amplifier
- Magnitude response and phase response
- Bode plots
- Classification of amplifiers based on their frequency response