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
  \[ x_o(t) = A \cdot x_i(t) \]
- Non-scalar or non-uniform amplification is called **distortion**
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. \( |v_{out_{MAX}}(t)| \leq VDD - VSS \)

- If input is too large, output clamps \( \Rightarrow \text{gain saturation} \)
Transfer Characteristic(1)

- Plot of amplifier output versus amplifier input

\[ V_{out} \]
\[ V_{in} \]

Slope is A

\[ +L \]
\[ -L \]
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)

Transfer Characteristic

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

Amplifier Output
Operating Point (3)

- 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:

\[
v_D(t) = 1.0 + 0.25 \sin(\omega t)
\]

\[
= V_D + v_d(t)
\]
Amplifier Classification

- Four types:

<table>
<thead>
<tr>
<th></th>
<th>Input</th>
<th>Output</th>
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<tbody>
<tr>
<td>Voltage</td>
<td>Voltage</td>
<td>Voltage</td>
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<tr>
<td>Current</td>
<td>Current</td>
<td>Current</td>
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<td>Transconductance</td>
<td>Voltage</td>
<td>Current</td>
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<tr>
<td>Transresistance</td>
<td>Current</td>
<td>Voltage</td>
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</tbody>
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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

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

\[ A_{V1} = \frac{v_{out}}{v_i} = \frac{R_L}{R_L + R_O} \left( A_{VO} \right) \]

\[ A_{V} = \frac{v_{out}}{v_i} \cdot \frac{v_i}{v_{IN}} = \frac{R_i}{R_i + R_S} \cdot \frac{R_L}{R_L + R_O} \left( A_{VO} \right) \]

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

\[ A_V \text{ maximized with large } R_{IN} (R_i), \text{ and small } R_{OUT} (R_O) \]
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

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

\[ A_{I1} = \frac{I_O}{I_i} = \frac{R_O}{R_O + R_L} \left( A_{IS} \right) \]

\[ A_I = \frac{I_O}{I_i} \cdot \frac{I_i}{I_S} = \frac{R_S}{R_S + R_i} \cdot \frac{R_O}{R_O + R_L} \left( A_{IS} \right) \]

- \( A_I < A_{IS} \) 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
- Two 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

\[
\begin{align*}
I_1 &= g_{11}V_1 + g_{12}I_2 \\
V_2 &= g_{21}V_1 + g_{22}I_2
\end{align*}
\]

- \(g_{11}\): 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 $i_{out}$

$$R_{OUT} = \frac{v_{out\mid open-circuit}}{i_{out\mid short-circuit}}$$

- 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...

$$A_V = \frac{v_{out}}{v_{IN}} = \frac{R_L}{R_L + R_{O2}} \cdot A_{VO2} + \frac{R_i2}{R_i2 + R_{O1}} \cdot A_{VO1} + \frac{R_i1}{R_i1 + R_S}$$
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…

Introduction to Analog and Digital Electronics 1.25
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.

\[ v_o = V_i \sin \omega t \]

\[ v_o = V_o \sin (\omega t + \phi) \]

- Ratio of \( V_o \) to \( V_i \) is the amplifier gain at the test frequency.
- The Transfer function of an amplifier is: \( T(\omega) = \frac{V_o(\omega)}{V_i(\omega)} \)
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 \(20\log|T(\omega)|\) 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 $j\omega L$ and C has the impedance of $1/jC\omega$
- In many cases complex frequency variable of $s$ is used instead of $\omega$, $\rightarrow sL$ and $1/sC$

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

- Replacing $s$ by $j\omega$ 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)
STC Network-Bode Plots

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

- High-pass STC
- Log scale axis
- 3 dB frequency or Corner frequency
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 \(1/jC\omega\) is very large
  - Resulting in zero gain at DC
  - They are not used in ICs

A capacitive-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