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UPDATED HOMEWORK ASSIGNMENT 1:
DUE WEDNESDAY, APRIL 14 BEFORE CLASS

Note, the textbook provides numerical solutions to most problems:

1) 1.48
2) 1.51
3) 1.56
4) 1.58
5) 1.67
6) 1.68
7) 3.10
8) 3.20

- Review Appendix E of Sedra and Smith: Single Time Constant Circuits
A primary engineering system goal is to acquire signals from the physical environment, process these signals and then use these results for monitoring and controlling the physical world. A related goal is for communication: the process of generating signals that may propagate through infrastructure (that may be wireline cable systems) or through free space and be received at remote locations.

Signals are created by transducers

- Examples
  1) Electromagnetic Antenna

![Electromagnetic Antenna](image1)

Figure 1. NASA/JPL Goldstone Deep Space Network Antenna

2) Acoustic Transducer (Microphone, Speaker)

![Acoustic Transducer](image2)

3) Biomedical Sensors and Systems

![Biomedical Sensors and Systems](image3)

Figure 2. Biomedical Sensors and Systems: Microaccelerometer and Medical Pacemaker Implant
4) Automotive Chemical Sensor

![Automotive Exhaust Gas Oxygen Sensor](image)

**Figure 3. Automotive Exhaust Gas Oxygen Sensor**

- Transducer signals are:
  - Continuous in time
    - Voltage, Current,
    - Variable Resistance, Capacitance, Inductance,

- Transducer signals may be weak:
  - Absorbed power by antenna may be $10^{-12}$W
  - Seismometer output may be $10^{-9}$V

- Source impedances may be large
  - Example: biomedical

- Bandwidth (Data Rate) may be high
  - Communication systems

- Two signal classes: Analog and Digital
  - Analog Signals
    - Analog signals are “analogs” of physical phenomena
  - Analog signal processing:
    - Detection
    - Amplification
    - Filtering
  - Analog signals appear as important problems whenever a transducer appears, or a signal is to be communicated (across a chip or to a spacecraft)

- Digital Signals
  - A digital signal is obtained by sampling an analog signal, and computing a discreet representation of the equivalent of the signal

- Analog signals may be *converted* to digital signals for computation
• Digital signals may be converted to analog signals for driving transducers

ANALOG CIRCUITS, DIGITAL CIRCUITS, AND COMPUTER ENGINEERING

• Digital circuits are composed of fundamental analog components, specifically transistor circuits, for logic operations
• Analog circuit design appears in computer engineering both as a fundamental element in digital circuit subsystems and also in applications including communication systems.
• EE115A provides background for both digital circuits (EE115C) and analog circuits (EE115B).

ANALOG SIGNAL PROCESSING AND AMPLIFIER BACKGROUND

• Amplifiers are required for detecting and processing signals for monitoring, computation, and control.
• The amplifier is the fundamental analog signal processing element and the target of analog design.
• Amplifiers process signals and may be used to increase (or decrease) the amplitude of current and voltage signals, and contribute power delivery capability to a signal processing chain.
• Amplifiers may also be used to compose analog filters for shaping system frequency response, or composing digital systems.
• Amplifier History
  o Pre-History of analog amplifier circuits
  o Only passive, linear (R, L, C) devices were available prior to 1880
  o Such networks may only absorb, not deliver energy.
  o The concept of amplification (increasing the amplitude of a signal) could not be considered
  o In about 1850, the first “spark gap” amplifiers appeared
  o Heinrich Hertz used these devices in 1887 to demonstrate communication with electromagnetic waves.
  o Marconi developed the concept of amplifier “biasing” for the spark gap receiver.
    ▪ This performance advance enabled communication over 10s of
In 1912, the Titanic, used its spark gap transmitter to send the first SOS signal and the message: “Come at once. We have struck a berg.”

- In 1912, the Titanic, used its spark gap transmitter to send the first SOS signal and the message: “Come at once. We have struck a berg.”

- Vacuum tube amplifiers, using phenomena first observed by Edison appeared in 1900.

Amplifier technology in early computer engineering
- 1930-1945 Alan Turing and electromechanical computation
- 1940 Vacuum tube based logic circuits
- 1946 Bell Laboratories launches a program to develop a “semiconductor amplifier”
- 1950 – 1970 Discrete transistor technology
- 1960 Integrated circuit
- 1965 Semiconductor memory
- 1969 Microprocessor
- Presently: Integrated circuits combine $10^8$ devices

Figure 4. Evolution of Intel microprocessor systems

Figure 5. Evolution of Intel microprocessor systems

- Modern Digital and Analog Integrated Circuit Technology
AMPLIFIER GAIN

- Amplifiers may be designed and operated to provide linear response – forming a “linear amplifier”.
- Amplifiers may provide Gain such that an input or voltage or current induces an output voltage or current.
- Amplifier circuit symbols for differential or single-ended amplifiers appear:

![Amplifier Circuit Symbols]

- Four different amplifier types depending on whether current or voltage appears at input or output.

\[
\begin{align*}
  v_O &= A_v v_i \\
  v_O &= H_i i_i \\
  i_O &= G v_i \\
  i_O &= A_i i_i
\end{align*}
\]

- The ratio of input to output signal is Gain: \( A_v, H, G, A_i \) (These values may be positive or negative)
- Note, in general, Gain may depend on voltage and current input value, power supply voltage values, signal frequency
- An amplifier may be terminated with (connected to) a load which absorbs power. For example, an audio amplifier may drive a speaker (transducer) system. The amplifier may produce a power gain.

![Amplifier and Load Diagram]

\[
\begin{align*}
  v_O i_O &= A_p v_i i_i \\
  p_O &= A_p p_i
\end{align*}
\]

- Note: The source of power to be delivered to an output load is from the Amplifier power supplies.
AMPLIFIER GAIN: DECIBEL MEASURE

- It is useful to express Gain and variations in gain in terms of ratios. The logarithm of ratios is also a useful means for describing Gain. (This is used throughout Electrical Engineering to describe Gain and Loss). The decibel (or dB unit) is used for describing current and voltage gain, as well as power gain.

- Conventional definitions for measuring power and voltage gain. Logarithmic measure is useful for expressing ratios of power and voltage values.
  - Voltage Gain (dB) = 20 log₁₀ |AV|
  - Current Gain (dB) = 20 log₁₀ |AI|
  - Power Gain (dB) = 10 log₁₀ |AP|

AMPLIFIER SATURATION

- Just as was discussed in EE10, amplifiers are supplied with power supply voltage values. The maximum range of operation of the amplifier output is no greater than these power supply values.

- Amplifier linear operation may only occur within an available operating range. The lowest value of output voltage for which linear operation is allowed may be \( V_{L^-} \) and the largest value is \( V_{L^+} \)

- Be definition, this limits input signal range, if linear operation is desired. This will be
  \[ V_{L^-} < A_f v_i < V_{L^+} \]

- This will be demonstrated below.

Figure 6. A MOSFET transistor demonstration.
Figure 7. MOSFET Drain Current vs Gate Voltage

Figure 8. The Transistor Operating Characteristics: Drain Current vs Source-Drain Voltage for varying Gate Voltage

Figure 9. The Common Source Amplifier. The left panel shows the circuit. The right panel shows the response with both input and output signals shown.
Figure 10. The affect of saturation on the Common Source Amplifier. Here, the input voltage amplitude is 1V.

Figure 11. The affect of bias variation on the Common Source amplifier. Here, the bias voltage setting is 0.5V, in contrast to the 1V value of Figure 6.
AMPLIFIER CIRCUIT MODELS

- A goal of 115A will be to develop methods for calculating properties of transistors that are embedded in amplifier circuits.
- Once known, the properties of the transistor, calculated at dc bias values will be used to build a small signal model.
- The small signal model contains only linear components.
- Important questions to answer with small – signal model
  - Gain
  - Input resistance
  - Output resistance
  - Frequency response
- With these parameters, amplifiers may be integrated into a system with a systematic design process – the entire system operation may be predicted.
FOUR AMPLIFIER TYPES

- Four different amplifier types depending on whether current or voltage appears at input or output.

\[
\begin{align*}
v_O &= A_v v_i \\
v_O &= Hi_i \\
i_O &= Gv_i \\
i_O &= A_i i_i
\end{align*}
\]

VOLTAGE AMPLIFIER

- \(R_i\) defines amplifier input current drawn by source.
- \(R_o\) defines output voltage dependence on output current.
- Output current appears when the amplifier is connected to a load, \(R_{LOAD}\).

INTEGRATING A VOLTAGE AMPLIFIER INTO A SYSTEM

- \(A_{VO}\) is the Open Circuit Voltage Gain – voltage generated in the absence of a load, \(R_{LOAD}\).
- \(A_{VO}\) is dimensionless.
- The presence of \(R_s\) along with finite \(R_i\) reduces \(v_i\).
- The presence of \(R_{LOAD}\) reduces \(v_O\).

\[
v_O = \frac{R_L}{R_o + R_L} A_{VO} v_i = \frac{R_L A_{VO}}{R_o + R_L} \cdot \frac{R_i}{R_i + R_s} v_s
\]
• $R_i$ and $R_o$ are critical, these will be calculated as small signal quantities.

• Problem 1.17 focuses on a computation of $R_i$ and $R_o$.

• Method for computing $R_o$ follows the method for computing Thevenin resistance:
  1. Replace input sources by their zero equivalents
     a. Voltage source replaced by short
     b. Current source replaced by open circuit
  2. Apply Test Voltage, $V_{\text{TEST}}$ at output terminals
  3. Compute $I_{\text{TEST}}$ induced by $V_{\text{TEST}}$
     \[ R_o = \frac{V_{\text{TEST}}}{I_{\text{TEST}}} \]

• Method for computing $R_i$ follows the method for computing Thevenin resistance:
  4. Replace output load by its zero equivalent
     a. Voltage output replaced by open circuit
     b. Current output replaced by short circuit
  5. Apply Test Voltage, $V_{\text{TEST}}$ at input terminals
  6. Compute $I_{\text{TEST}}$ induced by $V_{\text{TEST}}$
     \[ R_i = \frac{V_{\text{TEST}}}{I_{\text{TEST}}} \]

**CURRENT AMPLIFIER**

- $A_{\text{is}}$ is the Short Circuit Current Gain – current generated in the absence of a load, $R_{\text{LOAD}}$
- $A_{\text{is}}$ is dimensionless
- $R_i$ defines amplifier input voltage generated by source current
- $R_o$ defines output voltage dependence on output current
• Output voltage appears when the amplifier is connected to a load, $R_{\text{LOAD}}$.

• The presence of $R_{\text{LOAD}}$ reduces $i_o$ with respect to an amplifier where $R_{\text{LOAD}}$ is not present.

\[ i_o = \frac{R_o}{(R_o + R_L)} A_S i_i \]

• $R_i$ and $R_o$ are critical, these will be calculated as small signal quantities.

**Method for computing $R_o$ follows the method for computing Norton resistance:**

1. Replace input sources by their zero equivalents
   a. Voltage source replaced by short
   b. Current source replaced by open circuit
2. Apply Test Voltage, $V_{\text{TEST}}$ at output terminals
3. Compute $I_{\text{TEST}}$ induced by $V_{\text{TEST}}$

\[ R_o = \frac{V_{\text{TEST}}}{I_{\text{TEST}}} \]

**Method for computing $R_i$ follows the method for computing Thevenin resistance:**

1. Replace output load by its zero equivalent
   
   c. For voltage output, the load is replaced by open circuit
   
   d. For a current output, the load replaced by short circuit
2. Apply Test Voltage, $V_{\text{TEST}}$ at input terminals
3. Compute $I_{\text{TEST}}$ induced by $V_{\text{TEST}}$

\[ R_i = \frac{V_{\text{TEST}}}{I_{\text{TEST}}} \]

**TRANSCONDUCTANCE AMPLIFIER**
• $G_m$ is the Short Circuit Transconductance – current generated in the absence of a load, $R_{LOAD}$ due to a voltage input, $v_i$

• $G_m$ has units of conductance.

• Convenient model for transistor circuits.

• Bipolar transistor operates with three terminals, emitter, base, and collector.

• Transconductance, $g_m$

• Input resistance, $R_i \equiv r_\pi$

• Output resistance, $R_o \equiv r_o$

• As for other devices, these parameters depend on bias values.

**TRANSRESISTANCE AMPLIFIER**

• $G_m$ is the Open Circuit Transresistance – voltage generated in the absence of a load, $R_{LOAD}$ due to a current input, $i_i$

• $R_m$ has units of resistance.

**AMPLIFIER EQUIVALENTS**

• Amplifier equivalents may be constructed, as for source equivalents.

• Specifically, we may set the input and output signals of these amplifiers to be equal and then solve for the relationships between gains.

• For example, between Voltage and Current amplifiers, we set

\[ v_i = i_i R_i \]

and

\[ A_{VO} v_i = A_{IS} i_i R_o \]

• So,

\[ A_{VO} = A_{IS} \left( \frac{R_o}{R_i} \right) \]

• For example, between Voltage and Transconductance amplifiers, we set

\[ A_{VO} v_i = G_m v_i R_o \]

• So,

\[ A_{VO} = G_m R_o \]
AMPLIFIER FREQUENCY RESPONSE

- Amplifier frequency response is one of the most important determinators of amplifier value.
  - Frequency response of RF circuits may determine feasibility of wireless communication systems
  - Frequency response of digital circuits determines computing performance
  - Frequency response of analog signal processing for audio may determine the quality of audio instrumentation and products
- A focus of EE115C will be frequency response (time and frequency domain analysis) for digital circuits
- A focus of EE115B will be frequency response for analog circuits
- For EE115A, we must develop the capability to recognize the nature of amplifier frequency response types.
- This will be important to us in designing and analyzing small signal circuits
- Consider the directly coupled or dc amplifier architecture below. This circuit supports gain for “dc” static signals.

\[
\begin{align*}
\text{v}_i & \quad + \\
\text{v}_o & \quad + \\
\text{V}_{DD} & \quad - \\
\text{V}_{SS} & \quad - \\
\text{R}_{LOAD} & \quad - \\
\end{align*}
\]

- It is often required that the input signal source, \(v(t)\), contains a voltage signal that is a superposition of a large dc (static) voltage, \(V_i\), and a small ac (time dependent) signal, \(v(t)\).
  
  \[
  n(t) = V_i + v(t)
  \]
- It is then additionally important to isolate the amplifier from the influence of \(V_i\) (note that \(V_i\) may carry no useful information). Thus, a capacitor may be introduced to enable transmission of time dependent signals, while “blocking” dc signal components.
- Consider the capacitively “ac coupled” amplifier, below. This includes a first order RC circuit (so-called single time constant circuit) at the input.
• Consider the capacitively coupled amplifier, below. This includes a first order R-C circuit (so-called single time constant circuit (STC)) at the input and output.

• We may now analyze the properties of the STC circuit, Transfer Function.

\[
T(\omega) = \frac{V_O(\omega)}{V_i(\omega)}
\]

• We will start with the “low pass” STC circuit.

• Now, we have the familiar differential equation, derived from node voltage analysis, for this circuit:

\[
v_i - v_o = RC \frac{d}{dt} v_o
\]

• We may use Laplace techniques for our analysis of the Transfer Function.

\[
T(s) \equiv \frac{v_o(s)}{v_i(s)} = \frac{1}{1 + sRC} = \frac{1}{1 + s \tau} = \frac{1}{1 + \frac{s}{\omega_o}}
\]

\[
\omega_o \equiv \frac{1}{RC} = \frac{1}{\tau}
\]

• Expressing the Transfer Function in physical frequency with \( s = j\omega \)
\[ |T(\omega)| = \frac{|v_o(\omega)|}{|v_i(\omega)|} = \frac{1}{\sqrt{1 + \left(\frac{\omega}{\omega_o}\right)^2}} \]

- A phase shift exists between the input and output signals. This is
  \[ \phi = -\arctan\left(\frac{\omega}{\omega_o}\right) \]

- We will also examine the “high pass” STC circuit.

\[ v_o - v_i = \frac{1}{RC} \frac{dv}{dt} (v_i - v_o) \]

- Again, we have the familiar differential equation, derived from node voltage analysis, for this circuit:

\[ T(s) = \frac{v_o(s)}{v_i(s)} = \frac{s}{s + RC} = \frac{1}{s + \frac{1}{s\tau} + \frac{\omega_o}{s}} \]

\[ \omega_o = \frac{1}{RC} = \frac{1}{\tau} \]

- Expressing the Transfer Function in physical frequency with \( s = j\omega \)

\[ |T(\omega)| = \frac{|v_o(\omega)|}{|v_i(\omega)|} = \frac{1}{\sqrt{1 + \left(\frac{\omega_o}{\omega}\right)^2}} \]

- A phase shift exists between the input and output signals. This is
  \[ \phi = \arctan\left(\frac{\omega_o}{\omega}\right) \]

- We can examine the behavior of these two circuit systems.

- We will select values of \( R \) and \( C \) such that \( \omega_o = 1/2\pi \). Then, the radial frequency, \( \omega_o = 1/RC = 2\pi \). Finally, since \( \omega_o = 2\pi f_o \), then the frequency, \( f_o = 1 \) Hertz

- This requires \( R = C = 0.399 \)

- Now, here is our low pass circuit implemented with PSpice.
• PSpice has been used to compute the Transfer Function

• PSpice has also been used to compute the Transfer Function in dB units:

\[ 20\log_{10}|T(\omega)| \]

• Note that at \( f = 1.0\)Hz, the Transfer Function amplitude has decayed by 3dB. It is at this frequency that the Transfer Function decays by a factor of \( \frac{1}{\sqrt{2}} \) below its dc value.

\[ |T(\omega = \omega_0)| = \frac{1}{\sqrt{1 + \left( \frac{\omega}{\omega_0} \right)^2}} = \frac{1}{\sqrt{2}} \]
• This is referred to as the 3dB frequency or “corner” frequency.
• Note also that for \( \omega >> \omega_0 \), then the Transfer Function decays as \( 1/\omega \)
• Now, we may also examine phase response, computed with PSpice:

![Phase Response Graph]

• Note that the phase shift is 45° at the frequency at which \( \omega = \omega_0 \).
• Continuing, here is our high pass circuit implemented with PSpice.

![High Pass Circuit Diagram]

• PSpice has also been used to compute the Transfer Function in dB units:
  \[
  20 \log_{10} |T(\omega)|
  \]
• Note that at \( f = 1.0 \text{Hz} \), the Transfer Function amplitude has increased to within 3dB of its infinite frequency value. It is at this frequency that the Transfer Function is a factor of \( \frac{1}{\sqrt{2}} \) below its dc value.

\[
|T(\omega = \omega_0)| = \frac{1}{\sqrt{1 + \left(\frac{\omega_0}{\omega_0}\right)^2}} = \frac{1}{\sqrt{2}}
\]

• This is also the 3dB frequency or “corner” frequency for a high pass circuit.
• Note also that for \( \omega \ll \omega_0 \), then the Transfer Function increases as \( 1/\omega \)
• Now, we may also examine phase response, computed with PSpice:

![Graph showing phase response](image)

• Note that the phase shift is \( 45^\circ \) at the frequency at which \( \omega = \omega_0 \).
• Now, note the “low” and “high” pass nature of the signal transmission for these two circuits.

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**STC CIRCUIT CLASSIFICATION**

• In EE115A, it will be important to be able to recognize Low Pass and High Pass structures.
• A rule for determining whether a circuit system is high pass or low pass is to test the behavior of the circuit output under conditions of 1) Open Circuit Capacitors and, 2) Short Circuit Capacitors.
• If a circuit has finite output value for its capacitors being replaced by Open Circuits, then this is a Low Pass structure.

• If a circuit has zero output value for its capacitors being replaced by Open Circuits, then this is a High Pass structure.

• If a circuit has finite output value for its capacitors being replaced by Short Circuits, then this is a High Pass structure.

• If a circuit has zero output value for its capacitors being replaced by Short Circuits, then this is a Low Pass structure.
AMPLIFIER FREQUENCY RESPONSE: APPLICATION

Figure 12. A typical Transistor Amplifier (Common Source Amplifier). Note its directly coupled input and note also the capacitive load at the output.

Figure 13. Frequency response of output voltage, for the Common Source Amplifier of Figure 11.

Figure 14. A Common Source amplifier, as for Figure 11, but, with input coupling capacitance.
Figure 15. Gain (dB) for the amplifier of Figure 13. Note the low and high frequency behavior.

Figure 16. Phase Response for the amplifier of Figure 13.

AMPLIFIER APPLICATION: CMOS DIGITAL LOGIC

Figure 17. An Intel Pentium microprocessor silicon die. Also, a cross-sectional view of this device.
Figure 18. The CMOS Inverter is shown in the left panel. At the upper right, the input signal $V_{IN}$ is shown. At lower right, the output is shown.

Figure 19. A CMOS NOR gate is shown at the lower left. At upper right, the input signal $V_a$ is shown. At middle right, $V_b$ is shown. The NOR output is shown at lower right.