UNIVERSITY *of* DELAWARE

Chapter 1

Signals and Amplifiers

IN THIS CHAPTER YOU WILL LEARN

1. That electronic circuits process signals, and thus understanding electrical signals is essential to appreciating the material in this book.

2. The Thevenin and Norton representations of signal sources.

3. The representation of a signal as the sum of sine waves.

4. The analog and digital representations of a signal.

5. The most basic and pervasive signal-processing function: signal amplification, and correspondingly, the signal amplifier.

6. How amplifiers are characterized (modeled) as circuit building blocks independent of their internal circuitry.

7. How the frequency response of an amplifier is measured, and how it is calculated, especially in the simple but common case of a single-time constant (STC) type response.

1.1 SIGNALS

Signal

1. sign, indication
2. a: an act, event, or watchword that has been agreed on as the occasion of concerted action b: something that incites to action
3. something (as a sound, gesture, or object) that conveys notice or warning
4. a: an object used to transmit or convey information beyond the range of human voice b: the sound or image conveyed in telegraphy, telephony, radio, radar, or television c: a detectable physical quantity or impulse (as a voltage, current, or magnetic field strength) by which messages or information can be transmitted

http://www.merriam-webster.com/dictionary/signal

Definitions

Transducer

- Device that converts real world, or physical, signals into electrical signals.

Signal Processing

- Manipulation of signals to extract desired information.

Thevenin’s Theorem

http://en.wikipedia.org/wiki/Th%C3%A9venin%27s_theorem

In circuit theory, Thévenin's theorem for linear electrical networks states that any combination of voltage sources, current sources, and resistors with two terminals is electrically equivalent to a single voltage source *V* and a single series resistor *R*. For single frequency AC systems the theorem can also be applied to general impedances, not just resistors. The theorem was first discovered by German scientist Hermann von Helmholtz in 1853, but was then rediscovered in 1883 by French telegraph engineer Léon Charles Thévenin (1857–1926).

Norton’s Theorem

http://en.wikipedia.org/wiki/Norton%27s_theorem

Norton's theorem for linear electrical networks, states that any collection of voltage sources, current sources, and resistors with two terminals is electrically equivalent to an ideal current source, *I*, in parallel with a single resistor, *R*.

Norton's theorem is an extension of Thévenin's theorem and was introduced in 1926 separately by two people: Siemens & Halske researcher Hans Ferdinand Mayer (1895–1980) and Bell Labs engineer Edward Lawry Norton (1898–1983).

Appendix D

APPENDIX D

SOME USEFUL NETWORK THEOREMS

Introduction

In this appendix we review three network theorems that are useful in simplifying the analysis of electronic circuits: Thévenin's theorem, Norton's theorem, and the source-absorption theorem.

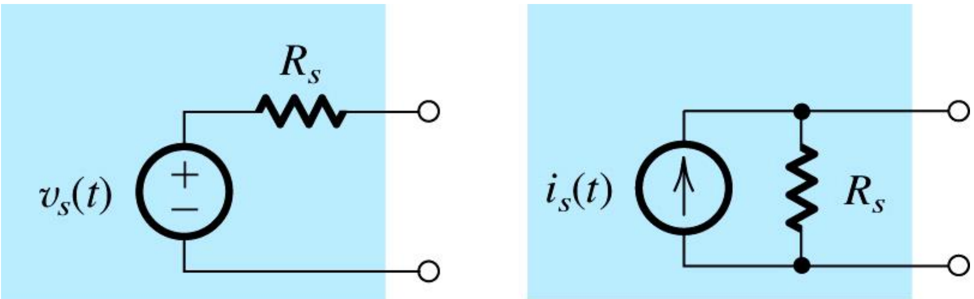
D.1 Thévenin's Theorem

Thévenin's theorem is used to represent a part of a network by a voltage source V_t and a series impedance Z_t, as shown in Fig. D.1. Figure D.1(a) shows a network divided into two parts, A and B. In Fig. D.1(b), part A of the network has been replaced by its Thévenin equivalent: a voltage source V_t and a series impedance Z_t. Figure D.1(c) illustrates how V_t is to be determined: Simply open-circuit the two terminals of network A and measure (or calculate) the voltage that appears between these two terminals. To determine Z_t, we reduce all external (i.e., independent) sources in network A to zero by short-circuiting voltage sources and open-circuiting current sources. The impedance Z_t will be equal to the input impedance of network A after this reduction has been performed, as illustrated in Fig. D.1(d).

D.2 Norton's Theorem

Norton's theorem is the *dual* of Thévenin's theorem. It is used to represent a part of a network by a current source I_n and a parallel impedance Z_n, as shown in Fig. D.2. Figure D.2(a) shows a network divided into two parts, A and B. In Fig. D.2(b), part A has been replaced by its Norton's equivalent: a current source I_n and a parallel impedance Z_n. The Norton's current source I_n can be measured (or calculated) as shown in Fig. D.2(c). The terminals of the network being reduced (network A) are shorted, and the current I_n will be equal simply to the short-circuit current. To determine the impedance Z_n, we first reduce the external excitation in network A to zero: That is, we short-circuit independent voltage sources and open-circuit independent current sources. The impedance Z_n will be equal to the input impedance of network A after this source-elimination process has taken place. Thus the Norton impedance Z_n is equal to the Thévenin impedance Z_t. Finally, note that $I_n = V_t/Z$, where $Z = Z_n = Z_t$.

Thevenin and Norton Forms



(a) (b)

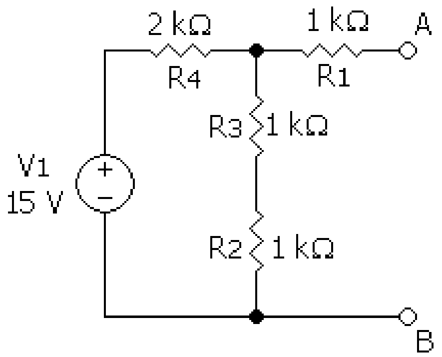
Figure 1.1 Two alternative representations of a signal source: **(a)** the Thévenin form; **(b)** the Norton form.

$$v_s(t) = R_s i_s(t)$$

Q: How are signals represented?

- **A: thevenin form** – voltage source **v**$_s(t)$ with series resistance R_S
  - preferable when R_S is low
- **A: norton form** – current source **i**$_s(t)$ with parallel resistance R_S
  - preferable when R_S is high

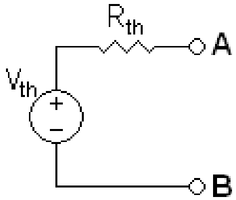
Norton and Thevenin Circuit Representations



$$R_{Th} = R_{No}$$

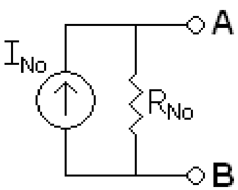
$$I_{No} = \frac{V_{Th}}{R_{Th}}$$

$$V_{Th} = I_{No} R_{No}$$



$V_{th} =$ ________________

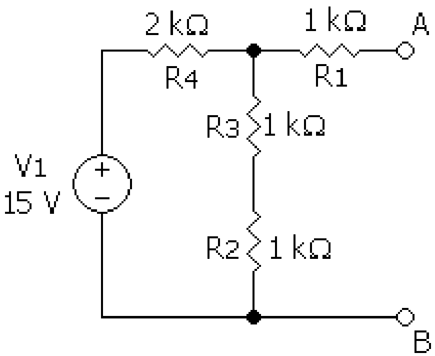
$R_{th} =$ ________________

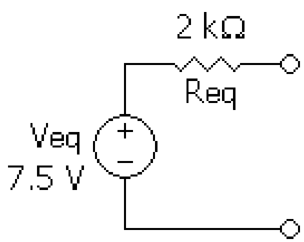


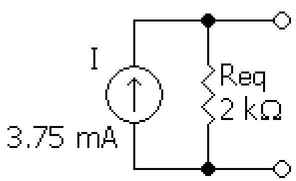
$I_{No} =$ ________________

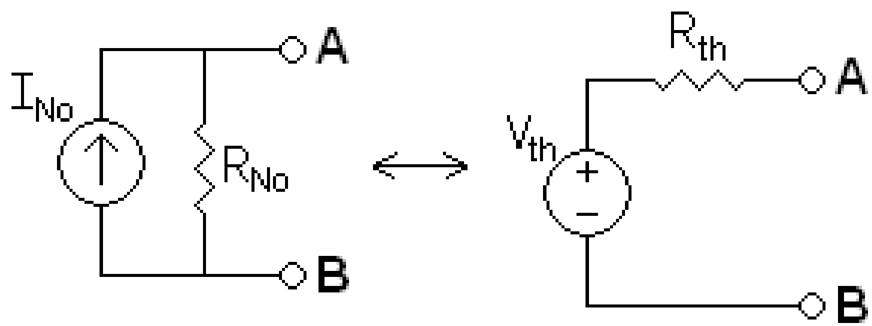
$R_{No} =$ ________________

Norton and Thevenin Circuit Representations







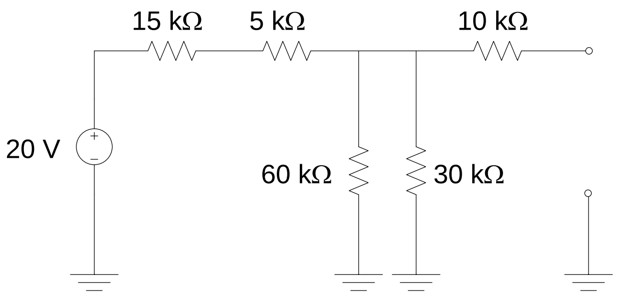


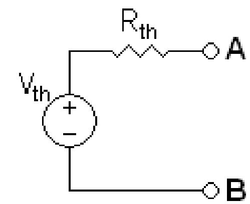
$$R_{Th} = R_{No}$$

$$I_{No} = \frac{V_{Th}}{R_{Th}}$$

$$V_{Th} = I_{No} R_{No}$$

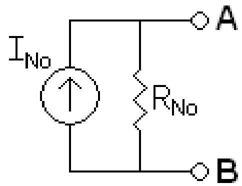
Norton and Thevenin Circuit Representations





V_{th} = ________________

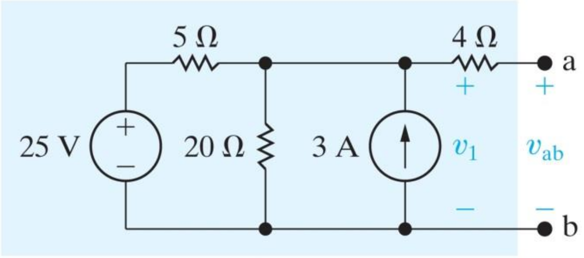
R_{th} = ________________

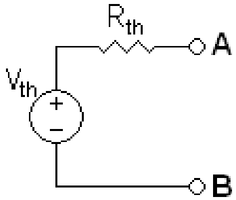


I_{No} = ________________

R_{No} = ________________

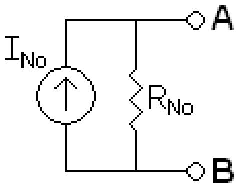
Norton and Thevenin Circuit Representations





V_{th} = ________________

R_{th} = ________________



I_{No} = ________________

R_{No} = ________________

Example 1.1

The output resistance of a signal source, although inevitable, is an imperfection that limits the ability of the source to deliver its full signal strength to a load. To see this point more clearly, consider the signal source when connected to a load resistance R_L as shown in Fig. 1.2. For the case in which the source is represented by its Thévenin equivalent form, find the voltage v_o that appears across R_L, and hence the condition that R_s must satisfy for v_o to be close to the value of v_s. Repeat for the Norton-represented source; in this case finding the current i_o that flows through R_L and hence the condition that R_s must satisfy for i_o to be close to the value of i_s.

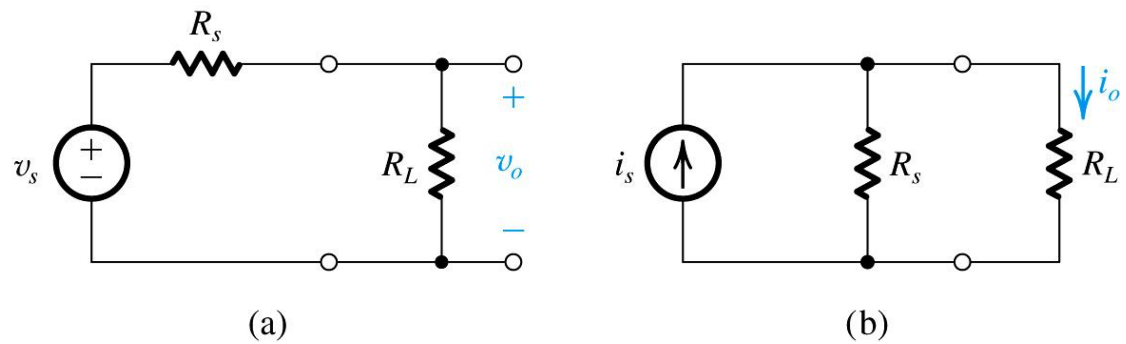
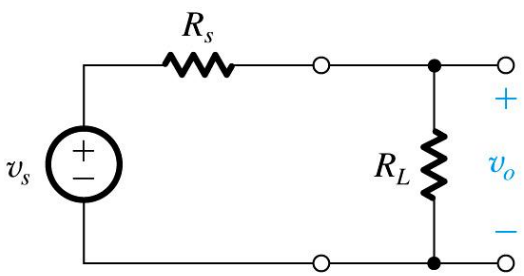


Figure 1.2 Circuits for Example 1.1.

Example 1.1

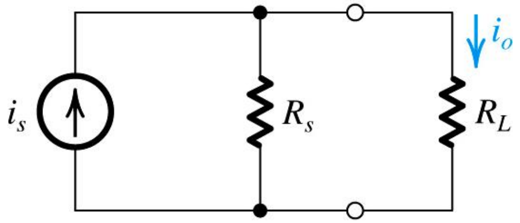


(a)

$$v_o = v_s \frac{R_L}{R_L + R_s}$$

For $v_o \approx v_s$ we need $R_L >> R_s$

Thus, for a source represented by its Thévenin equivalent, ideally $R_s = 0$, and as R_s is increased, relative to the load resistance R_L with which this source is intended to operate, the voltage v_o that appears across the load becomes smaller, not a desirable outcome.



(b)

$$i_o = i_s \frac{R_s}{R_s + R_L}$$

For $i_o \approx i_s$ we need $R_s >> R_L$

Thus for a signal source represented by its Norton equivalent, ideally $R_s = \infty$, and as R_s is reduced, relative to the load resistance R_L with which this source is intended to operate, the current i_o that flows through the load becomes smaller, not a desirable outcome.

Figure 1.2 Circuits for Example 1.1.

Example of a Time Variant Signal

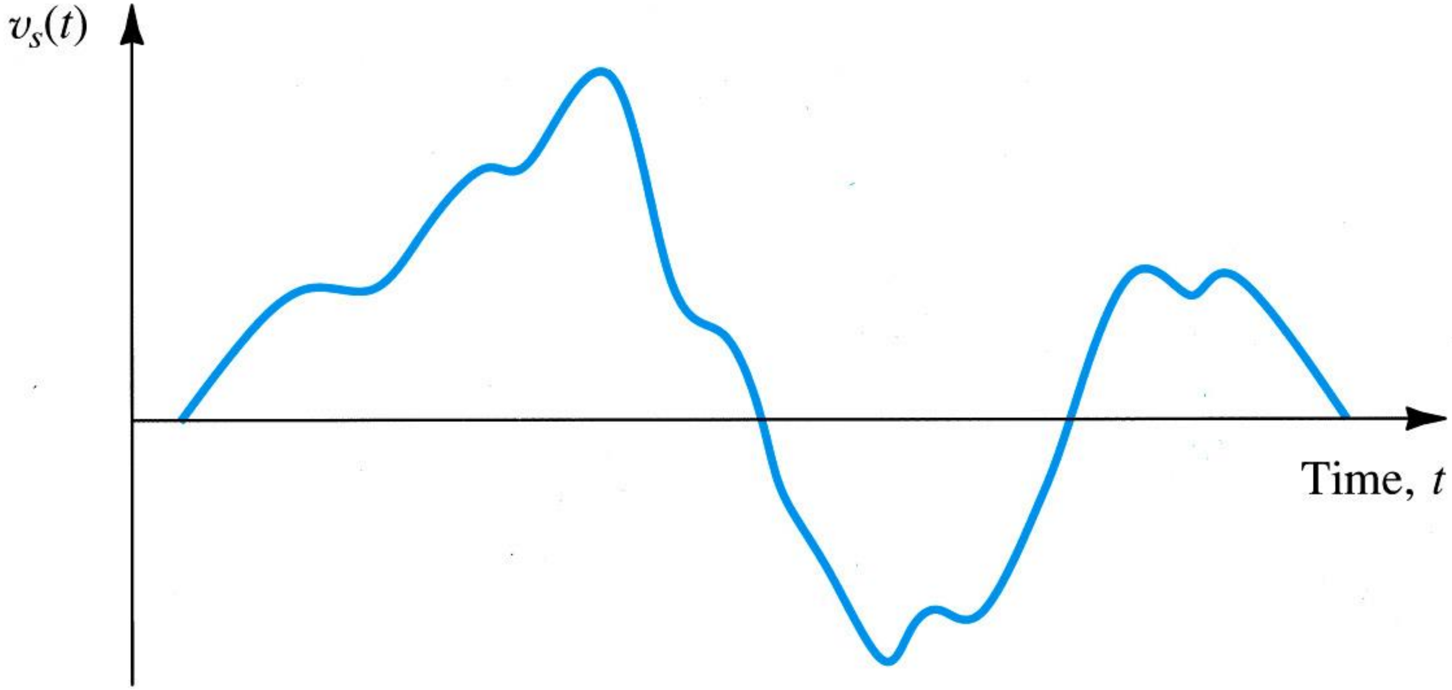


Figure 1.3 An arbitrary voltage signal $v_s(t)$.

1.2 FREQUENCY SPECTRUM OF SIGNALS

Sine-wave Voltage Signal

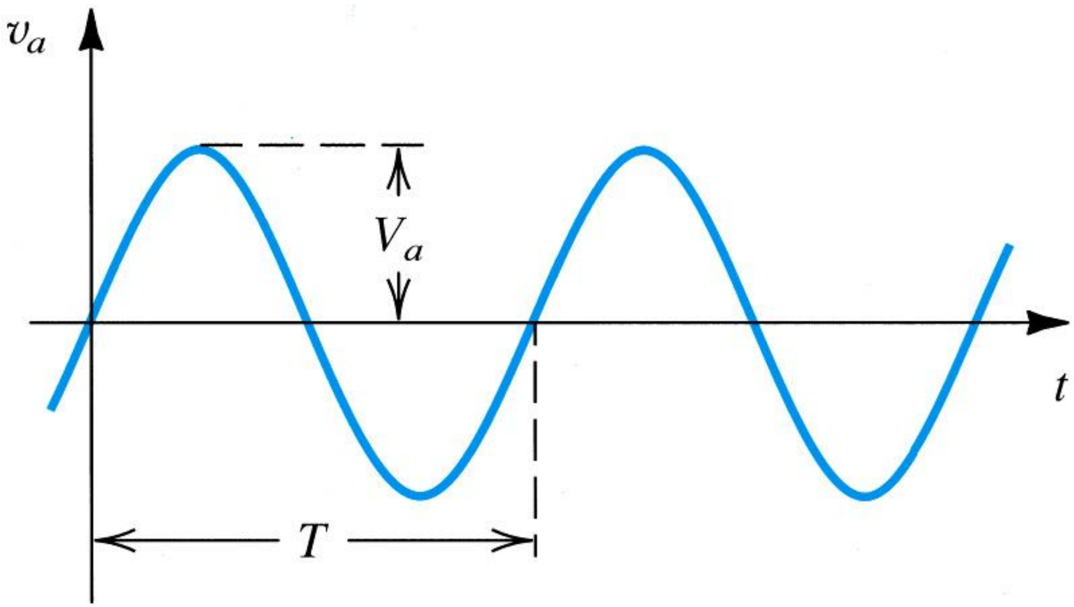


Figure 1.4 Sine-wave voltage signal of amplitude V_a and frequency $f = 1/T$ Hz. The angular frequency $\omega = 2\pi f$ rad/s.

$$v_a(t) = V_a \sin(\omega t)$$

where

V_a denotes the peak value or amplitude (volts)

ω denotes the angular frequency in radians per second (rad/s)

t is the time (s)

T is the period of signal (s)

f is the frequency (hertz or Hz)

$$f = \frac{\omega}{2\pi} = \frac{1}{T}$$

$$\omega = 2\pi f = \frac{2\pi}{T}$$

Definitions

Frequency Spectrum

- The frequency components that make a signal.

Fundamental Frequency

- The lowest frequency component of a periodic signal.

Fourier Transform

- Mathematical tool for converting between time domain and frequency domain.

Harmonic

- A multiple of the fundamental frequency.

Definitions

Octave

- Change in frequency by a factor of 2; i.e. a doubling or halving of the frequency.

Decade

- Change in frequency by a factor of 10; i.e. an order of magnitude increase or decrease in frequency.

Audio Band

- Frequency band from 20 Hz to 20 kHz which comprises the typical human audio spectrum.

Frequency Spectra of a Square Wave

$$v(t)=\frac{4V}{\pi}\left(\sin(\omega_0 t)+\frac{1}{3}\sin(3\omega_0 t)+\frac{1}{5}\sin(5\omega_0 t)+\ldots\right)$$

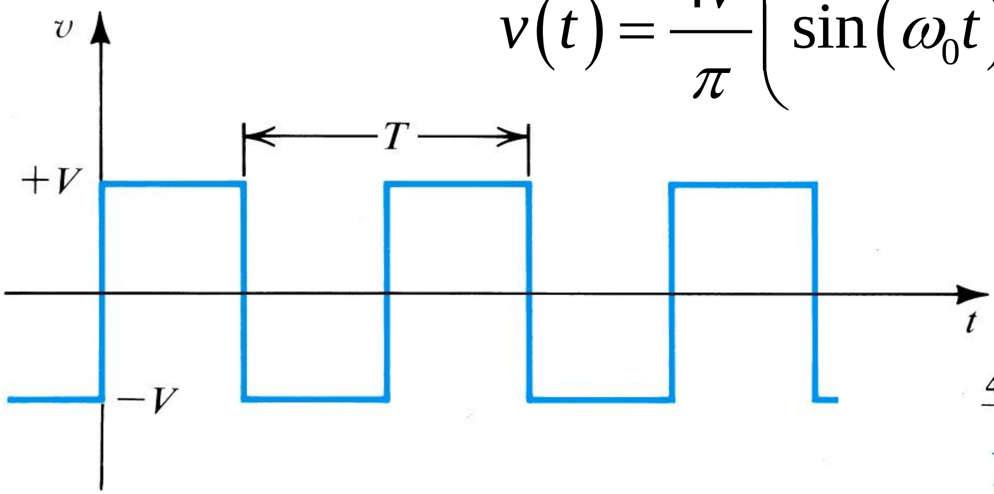


Figure 1.5 A symmetrical square-wave signal of amplitude V.

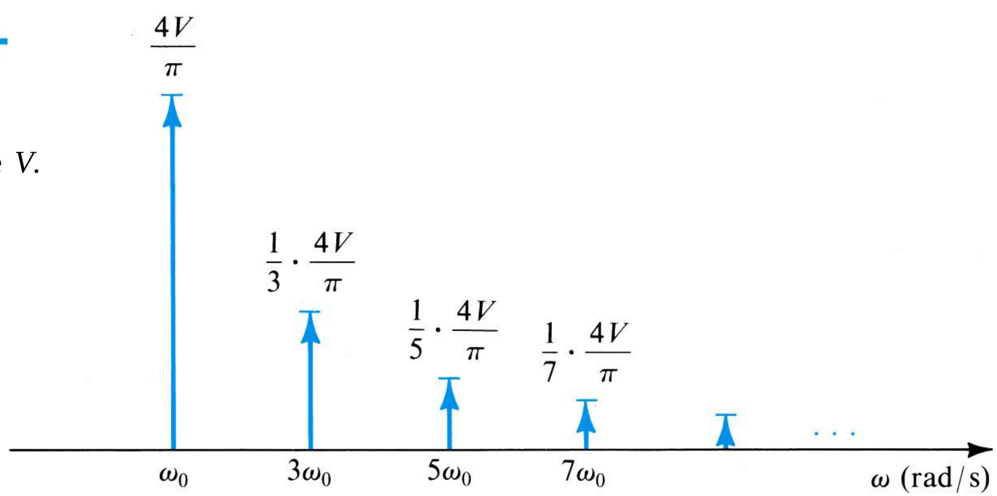
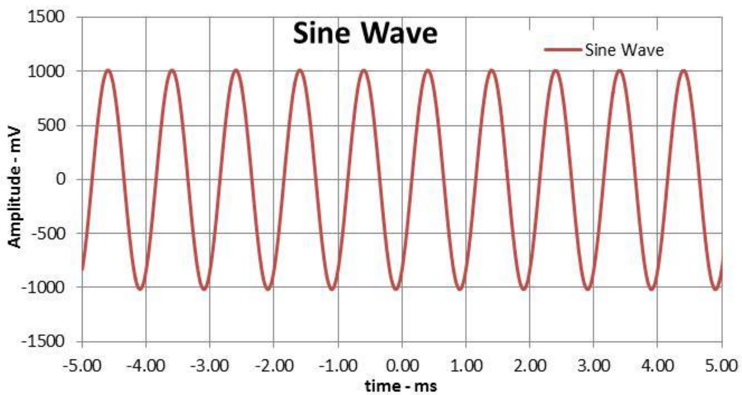
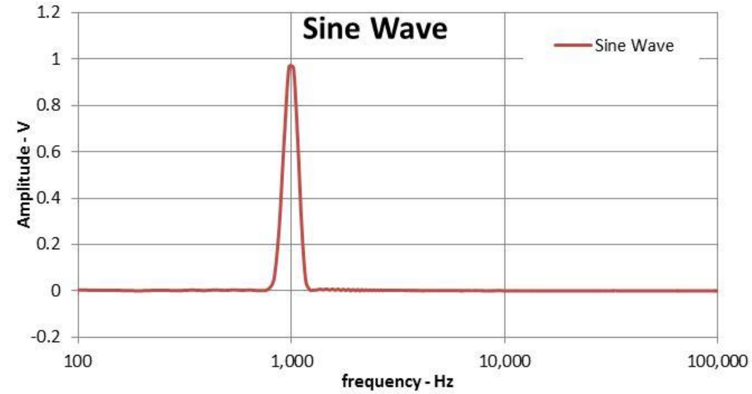
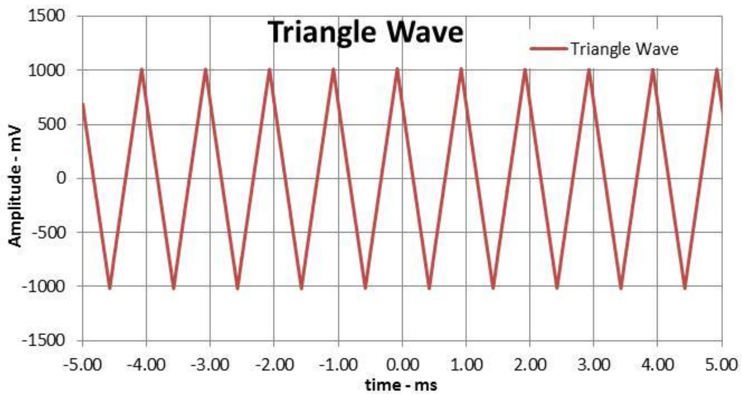


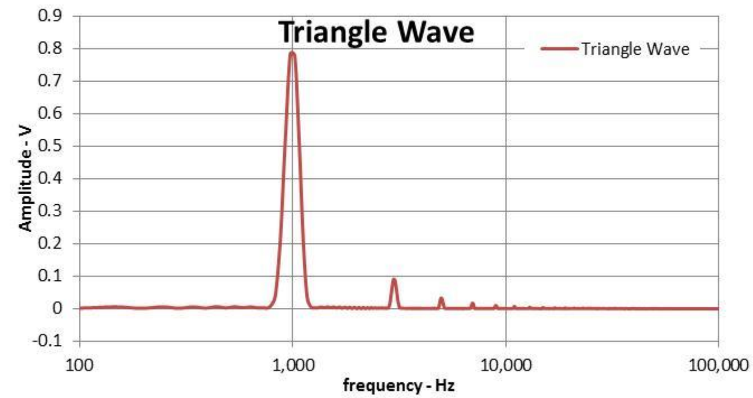
Figure 1.6 The frequency spectrum (also known as the **line spectrum**) of the periodic square wave of Fig. 1.5.

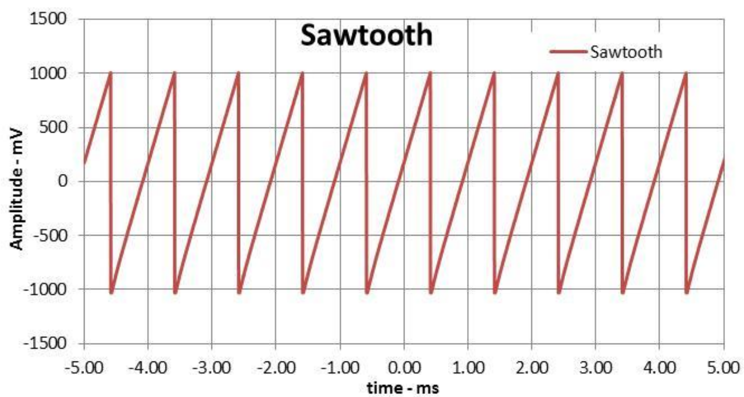
Frequency Spectra of a Square Wave

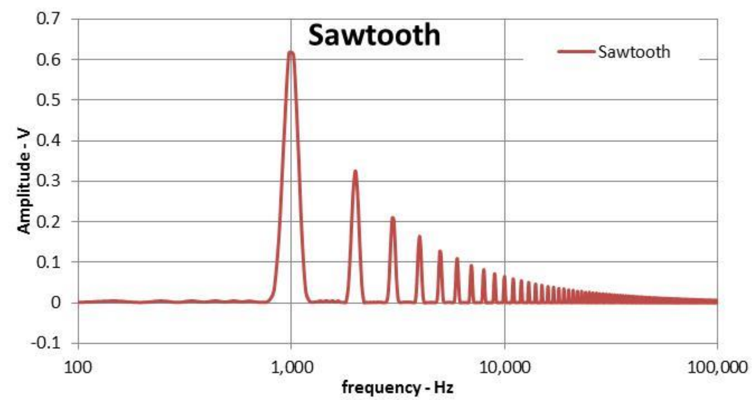

Sine Wave
Sine Wave
Amplitude - mV
time - ms
1500
1000
500
0
-500
-1000
-1500
-5.00 -4.00 -3.00 -2.00 -1.00 0.00 1.00 2.00 3.00 4.00 5.00


Sine Wave
Sine Wave
Amplitude - V
frequency - Hz
1.2
1
0.8
0.6
0.4
0.2
0
-0.2
100 1,000 10,000 100,000


Triangle Wave
Triangle Wave
Amplitude - mV
time - ms
1500
1000
500
0
-500
-1000
-1500
-5.00 -4.00 -3.00 -2.00 -1.00 0.00 1.00 2.00 3.00 4.00 5.00


Triangle Wave
Triangle Wave
Amplitude - V
frequency - Hz
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
100 1,000 10,000 100,000


Sawtooth
Sawtooth
Amplitude - mV
time - ms
1500
1000
500
0
-500
-1000
-1500
-5.00 -4.00 -3.00 -2.00 -1.00 0.00 1.00 2.00 3.00 4.00 5.00


Sawtooth
Sawtooth
Amplitude - V
frequency - Hz
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
-0.1
100 1,000 10,000 100,000

Time Domain/Frequency Domain

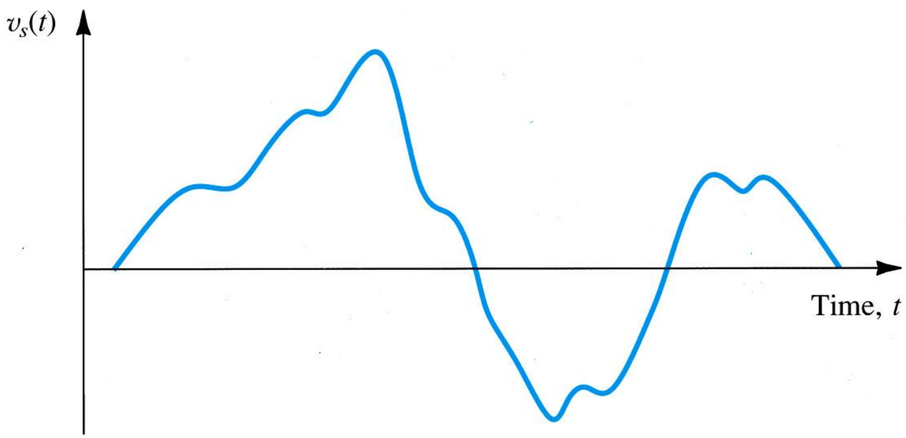


Figure 1.3 An arbitrary voltage signal $v_s(t)$.

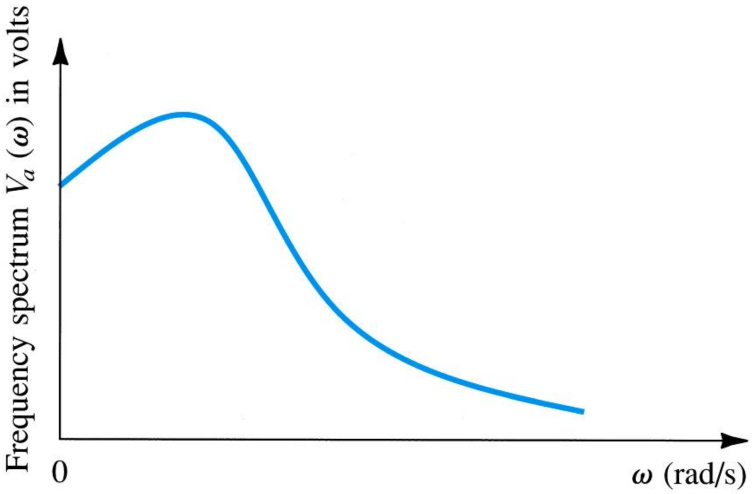


Figure 1.7 The frequency spectrum of an arbitrary waveform such as that in Fig. 1.3.

Time domain representation

$$v_a(\mathrm{t})$$

Frequency domain representation

$$V_a(\omega)$$

Homework #1

- Read Chapter 1
- Chapter 1 Problems: (due 2/13)
  - 1.15*
  - 1.23
  - 1.24
  - 1.28
  - 1.30

* Answers in Appendix L

- Choose Lab Partners
- Get Digilent Hardware and SIMetrix software

1.3 ANALOG AND DIGITAL SIGNALS

Definitions

Analog Signal

- Signal which has a magnitude that can take on any value.

Digital Signal

- a physical signal that is a representation of a sequence of discrete values.

Sampling

- Capturing the magnitude of a signal at equal intervals.

Discretized/Digitized

- Representing the magnitude by a number having a finite number of digits.

Sampling a Continuous-Time Analog Signal

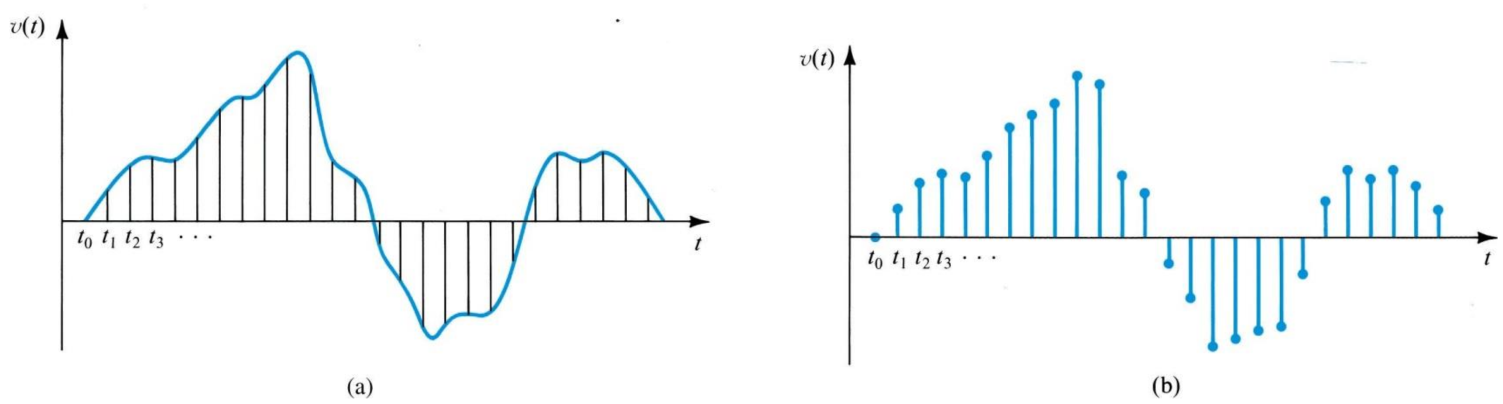


Figure 1.8 Sampling the continuous-time analog signal in **(a)** results in the discrete-time signal in (b).

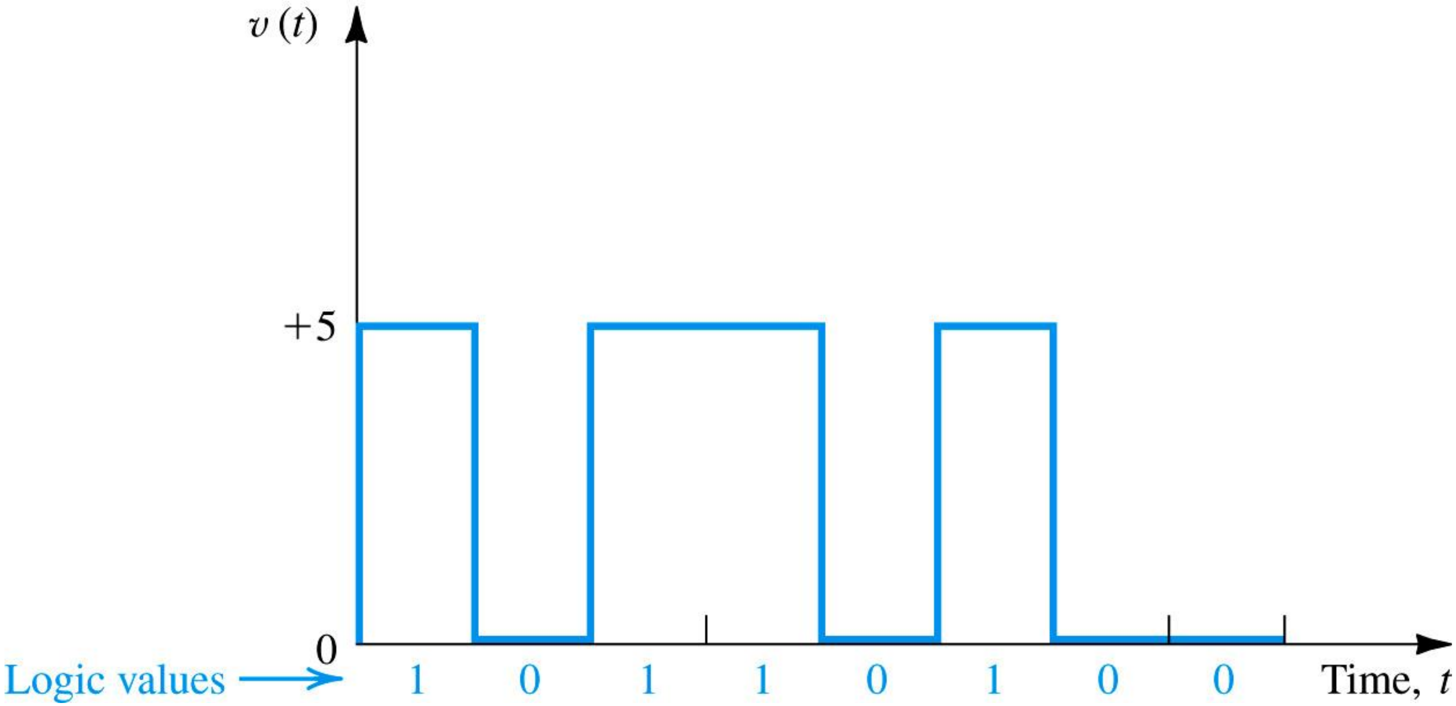


Figure 1.9 Variation of a particular binary digital signal with time.

Definitions

ADC

- Analog to digital converter.

DAC

- Digital to analog converter.

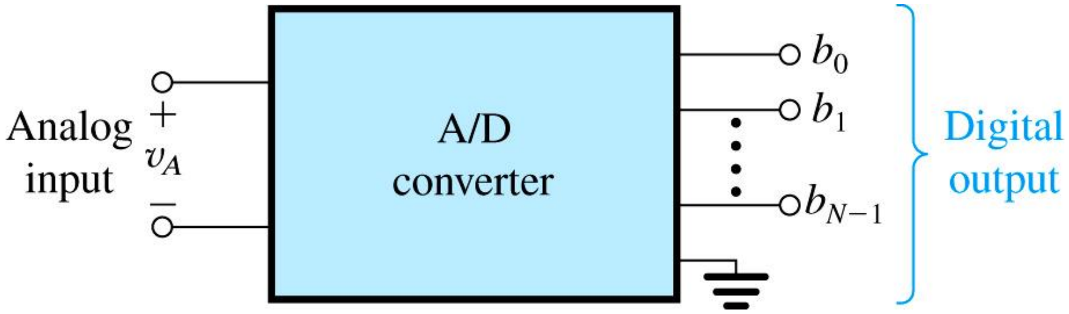
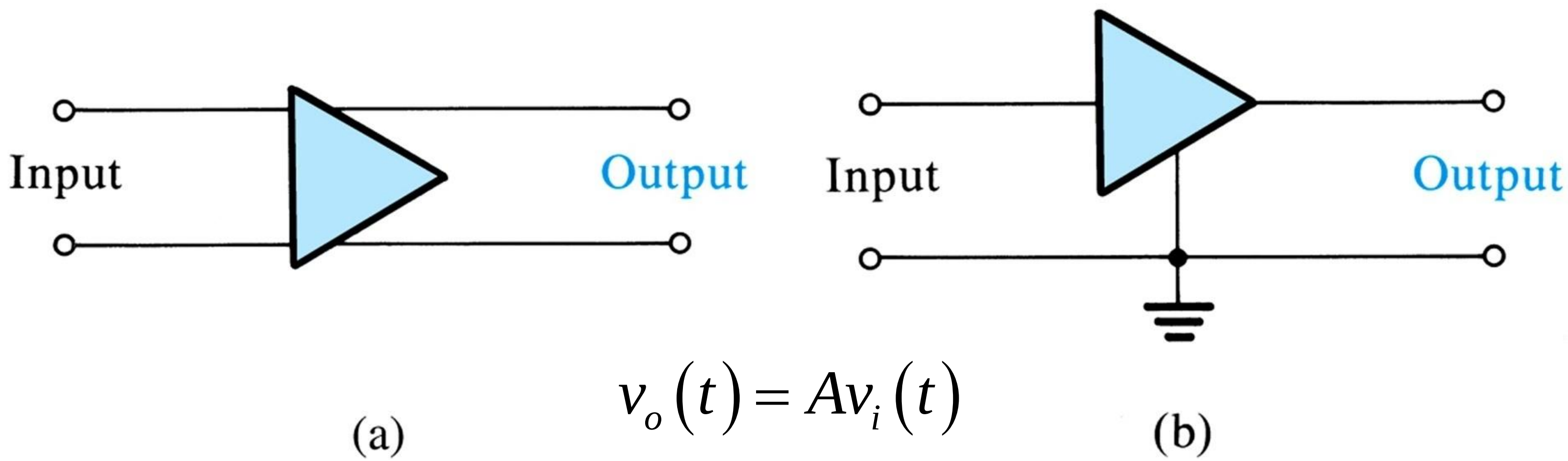


Figure 1.10 Block-diagram representation of the analog-to-digital converter (ADC).

1.4 AMPLIFIERS

Signal Amplification

From a conceptual point of view the simplest signal-processing task is that of signal amplification. The need for amplification arises because transducers provide signals that are said to be "weak," that is, in the microvolt (μV) or millivolt (mV) range and possessing little energy. Such signals are too small for reliable processing, and processing is much easier if the signal magnitude is made larger. The functional block that accomplishes this task is the signal amplifier.



$$v_o(t) = Av_i(t)$$

Figure 1.11 (a) Circuit symbol for amplifier. **(b)** An amplifier with a common terminal (ground) between the input and output ports.

Definitions

Linearity

- Measurement of how close the output signal is to a scaled version of the input.

Transfer Characteristic

- The output voltage as a function of input voltage.

Distortion

- Change in the waveform.

Decibel

- Log based ratio or measurement of gain.

Amplifier Gain

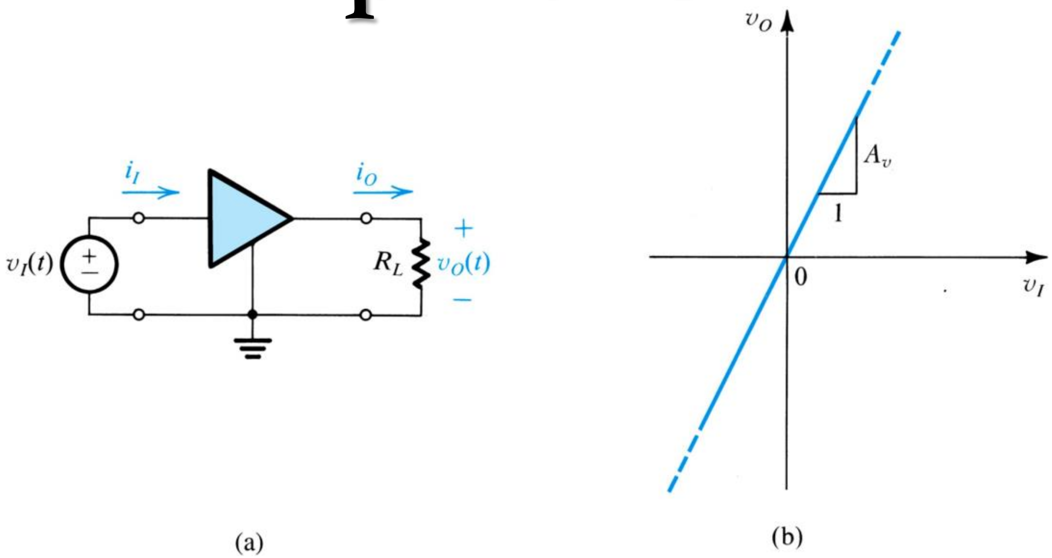


Figure 1.12 (a) A voltage amplifier fed with a signal $v_I(t)$ and connected to a load resistance R_L. (b) Transfer characteristic of a linear voltage amplifier with voltage gain A_v.

Voltage Gain $(A_v) = {v_o}/{v_i}$ Voltage Gain in dB $= 20\log|A_v|$

Current Gain $(A_i) = {i_o}/{i_i}$ Current Gain in dB $= 20\log|A_i|$

Power Gain $(A_p) = {v_o i_o}/{v_i i_i}$ Power Gain in dB $= 10\log|A_p|$

Amplifier Power Supplies

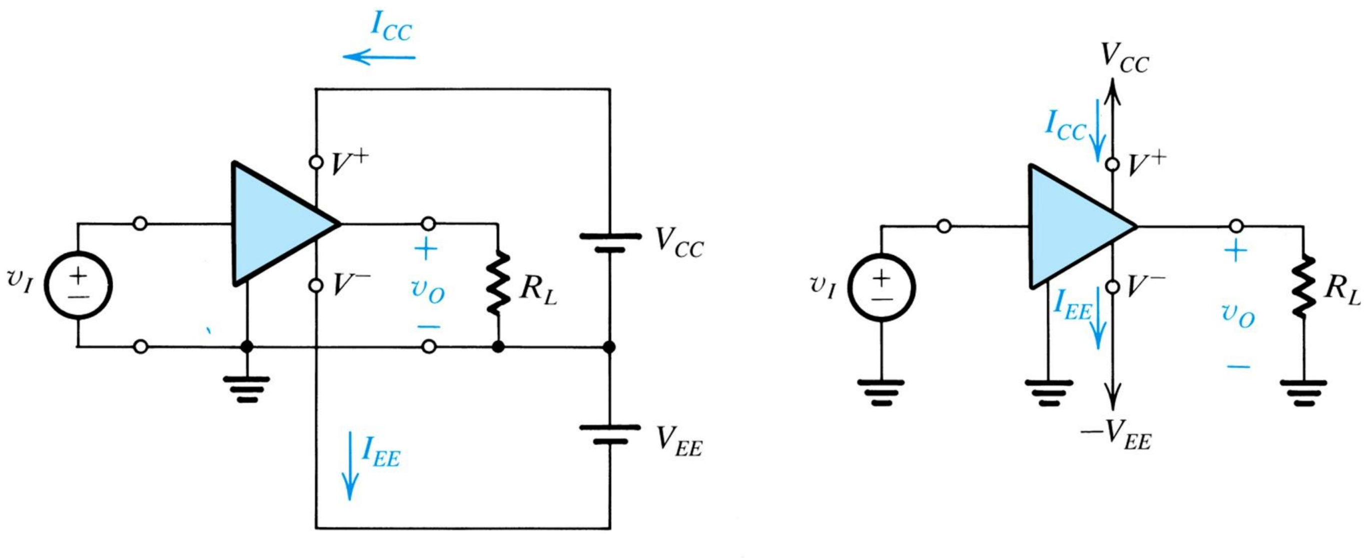


Figure 1.13 An amplifier that requires two dc supplies (shown as batteries) for operation.

DC power delivered to the amplifier $P_{dc} = V_{CC}I_{CC} + V_{EE}I_{EE}$

Power–balance equation for the amp $P_{dc} + P_I = P_L + P_{dissipated}$

Amplifier power efficiency $\eta = \frac{P_L}{P_{dc}} \times 100$

Amplifier Saturation

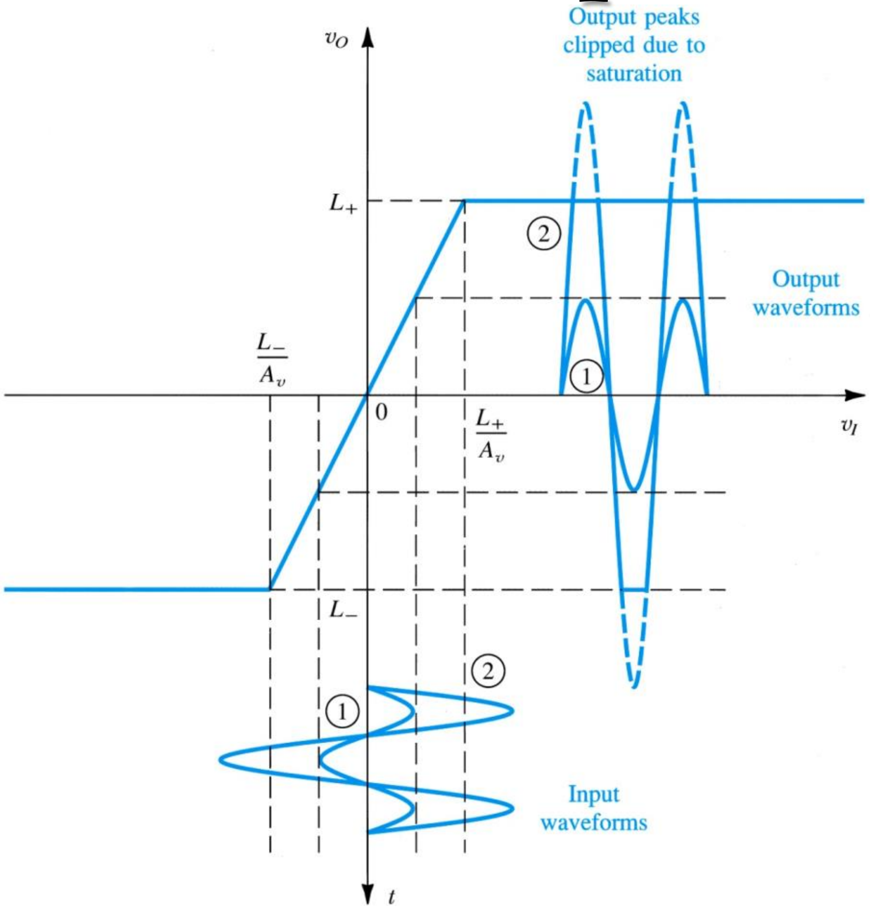


Figure 1.14 An amplifier transfer characteristic that is linear except for output saturation.

in order to avoid distorting the output signal waveform, the input signal swing must be kept within the linear range of operation

$$\frac{L_-}{A_v} \le v_I \le \frac{L_+}{A_v}$$

or

$$L_- \le v_o \le L_+$$

Symbol Conventions

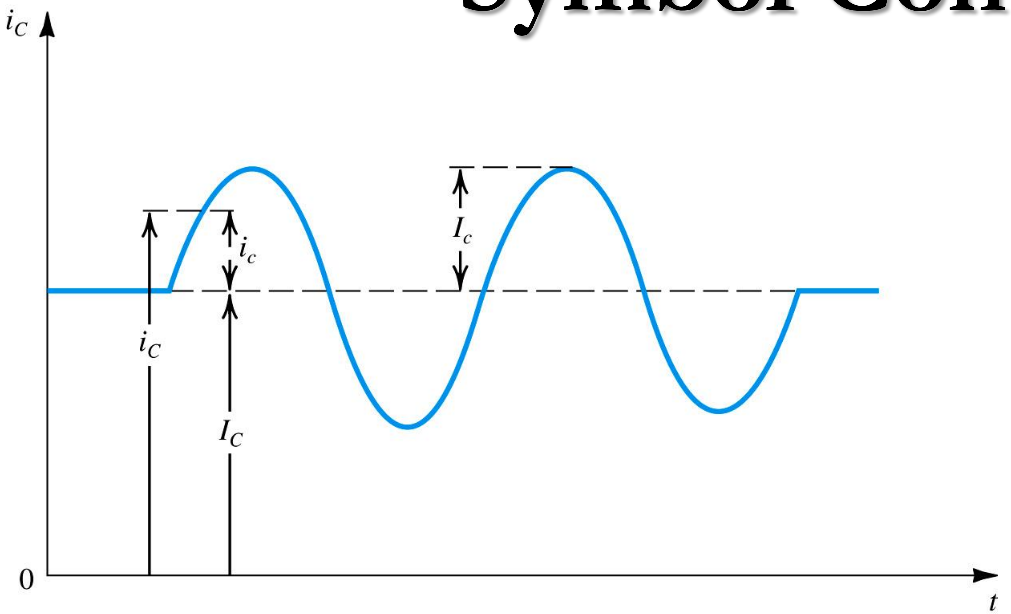


Figure 1.15 Symbol convention employed throughout the book.

Total instantaneous current

$$i_C(t) = I_C + i_c(t)$$

Signal current

$$i_c(t) = I_c \sin \omega t$$

Total instantaneous quantities are denoted by a lowercase symbol with uppercase subscript(s).

Direct-current, (dc) quantities are denoted by a uppercase symbol with uppercase subscript(s).

Incremental signal quantities are denoted by a lowercase symbol with lowercase subscript(s).

If the signal is a sine wave, then its amplitude is denoted by an uppercase symbol with lowercase subscript(s).

Finally, power supply voltages and currents are denoted by an uppercase letter with a double-letter uppercase subscript.

1.5 CIRCUIT MODEL FOR AMPLIFIERS

Definitions

Open-Circuit Voltage Gain

- Voltage gain of an unloaded amplifier.

Cascaded Amplifiers

- Multiple amplifiers connected in series.

Buffer Amplifier

- Amplifier with a high input resistance and a low output resistance with modest, or even unity, gain.

Unilateral

- Signal flow is unidirectional, from input to output.

Voltage Amplifiers

Open-circuit voltage gain

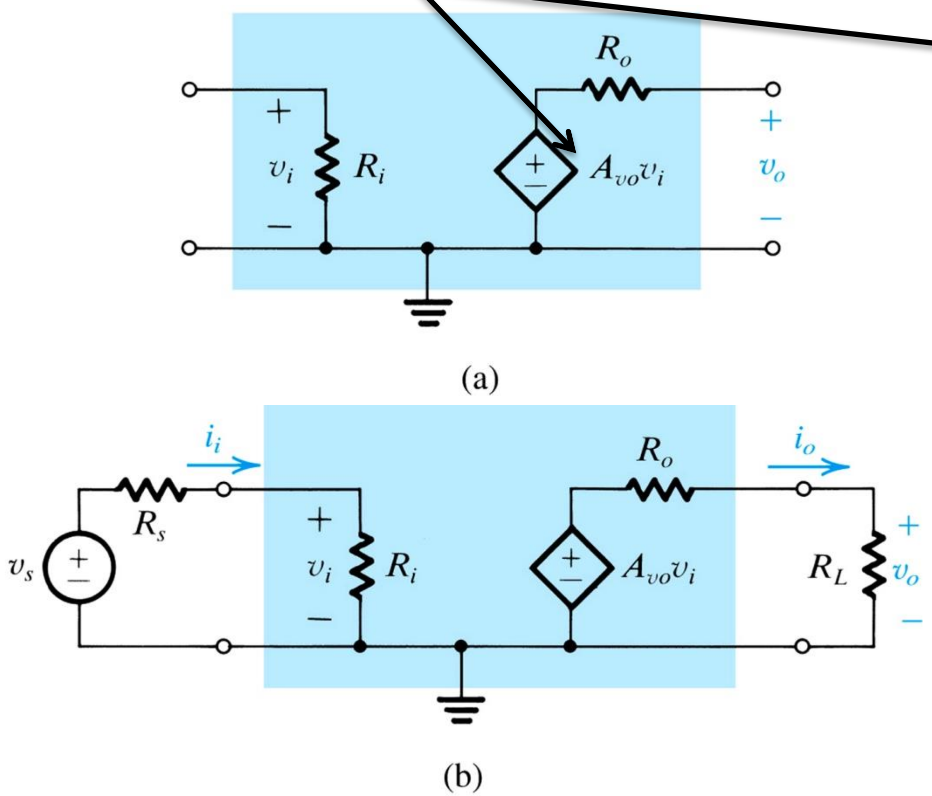


Figure 1.16 (a) Circuit model for the voltage amplifier. **(b)** The voltage amplifier with input signal source and load.

Using the voltage divider rule

$$v_o = A_{vo} v_i \frac{R_L}{R_L + R_o}$$

Thus the voltage gain of the amplifier is

$$A_v \equiv \frac{v_o}{v_i} = A_{vo} \frac{R_L}{R_L + R_o}$$

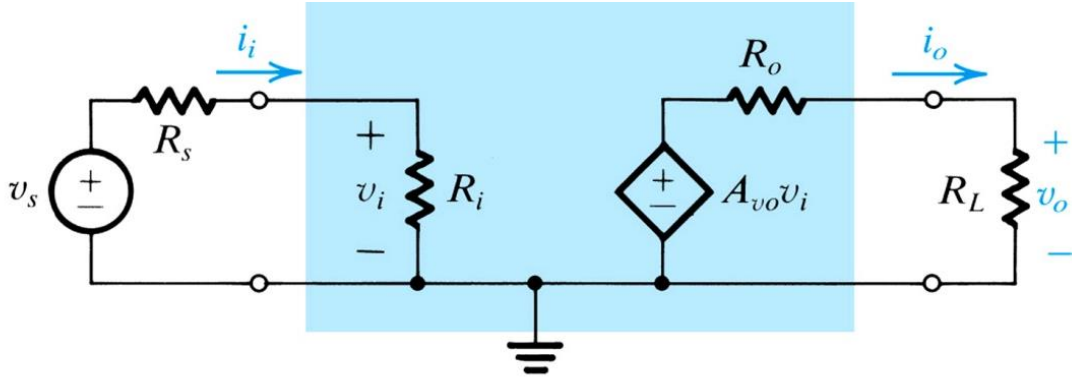
The input signal that reaches the amp is

$$v_i = v_s \frac{R_i}{R_i + R_s}$$

The overall voltage gain of the circuit is

$$G_v \equiv \frac{v_o}{v_s} = A_{vo} \frac{R_i}{R_i + R_s} \frac{R_L}{R_L + R_o}$$

Voltage Amplifier Models



(b)

Figure 1.16 (b) The voltage amplifier with input signal source and load.

$$v_i = v_s \frac{R_i}{R_i + R_s}$$

$$v_o = A_{vo} v_s \frac{R_i}{R_i + R_s} \frac{R_L}{R_L + R_o}$$

Important circuit characteristics

v_s	source voltage
R_s	source resistance
R_L	load resistance

Important amplifier characteristics

A_{vo}	voltage gain
R_i	input resistance
R_o	output resistance

Determining R_i and R_o

$$R_i = \frac{v_i}{i_i}$$

$$R_o = \frac{v_x}{i_x}$$

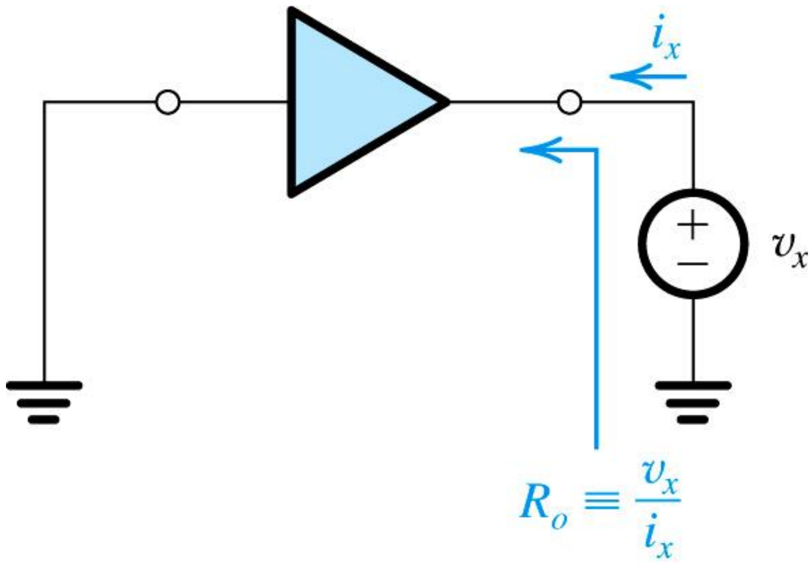
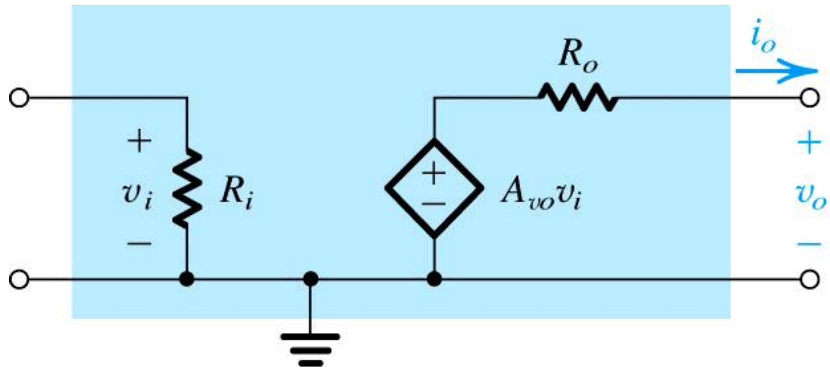


Figure 1.18 Determining the output resistance.

Voltage Amplifier



Open-Circuit Voltage Gain

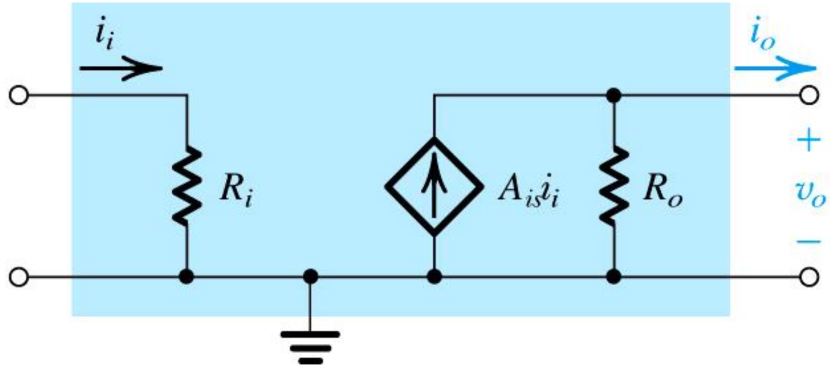
$$A_{vo} = \left.\frac{v_o}{v_i}\right|_{i_o=0} \left(\text{V/V}\right)$$

Ideal Characteristics

$$R_i = \infty$$

$$R_o = 0$$

Current Amplifier



Short-Circuit Current Gain

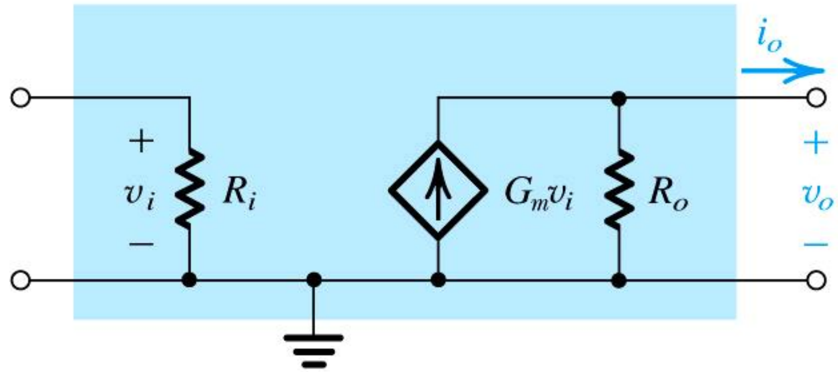
$$A_{is} = \left.\frac{i_o}{i_i}\right|_{v_o=0} \quad (\text{A/A})$$

Ideal Characteristics

$$R_i = 0$$

$$R_o = \infty$$

Transconductance Amplifier



Short-Circuit Transconductance

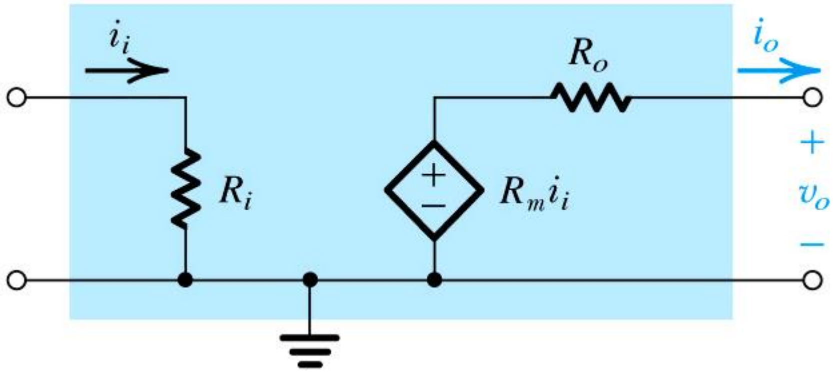
$$G_m = \left. \frac{i_o}{v_i} \right|_{v_o = 0} \left(\mathrm{A/V} \right)$$

Ideal Characteristics

$$R_i = \infty$$

$$R_o = \infty$$

Transresistance Amplifier



Open-Circuit Transresistance

$$R_m = \left.\frac{v_o}{i_i}\right|_{i_o=0} \quad (\mathrm{V/A})$$

Ideal Characteristics

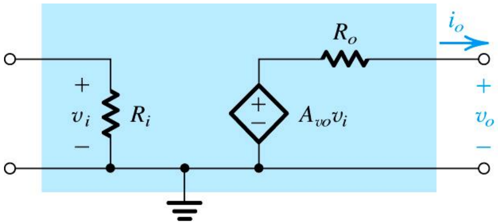
$$R_i = 0$$
$$R_o = 0$$

Types of Amplifiers

Ideal Characteristics

$$A_{vo} = \left.\frac{v_o}{v_i}\right|_{i_o=0} \quad (\mathrm{V/V})$$

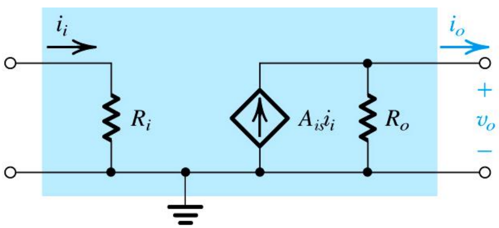
Open-Circuit Voltage Gain



$$R_i = \infty$$
$$R_o = 0$$

$$A_{is} = \left.\frac{i_o}{i_i}\right|_{v_o=0} \quad (\mathrm{A/A})$$

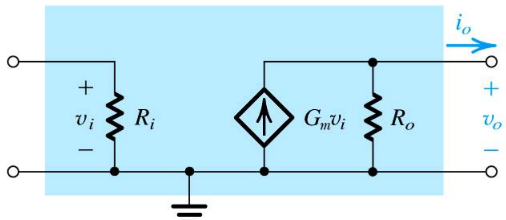
Short-Circuit Current Gain



$$R_i = 0$$
$$R_o = \infty$$

$$G_m = \left.\frac{i_o}{v_i}\right|_{v_o=0} \quad (\mathrm{A/V})$$

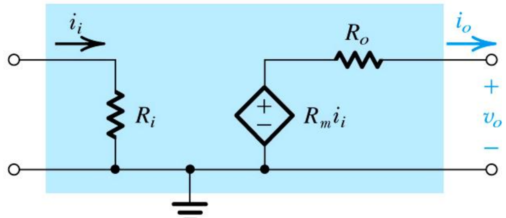
Short-Circuit Transconductance



$$R_i = \infty$$
$$R_o = \infty$$

$$R_m = \left.\frac{v_o}{i_i}\right|_{i_o=0} \quad (\mathrm{V/A})$$

Open-Circuit Transresistance



$$R_i = 0$$
$$R_o = 0$$

Table 1.1 The Four Amplifier Types

Relationships between 4 Amplifier Models

$$A_{vo} = \left.\frac{v_o}{v_i}\right|_{i_o=0} \quad (\text{V/V}) \quad \Rightarrow \quad A_{is} = \left.\frac{i_o}{i_i}\right|_{v_o=0} \quad (\text{A/A})$$

$$v_o = A_{vo} v_i \qquad v_o = i_o R_o = A_{is} i_i R_o = A_{is} \frac{v_i}{R_i} R_o$$

$$\frac{v_o}{v_i} = A_{vo} \qquad \frac{v_o}{v_i} = i_o R_o = A_{is} i_i R_o = A_{is} \frac{R_o}{R_i}$$

$$A_{vo} = A_{is} \frac{R_o}{R_i}$$

$$A_{vo} = G_m R_o \qquad A_{vo} = \frac{R_m}{R_i}$$

Cascading Amplifiers

- In real life, an amplifier is not ideal and will not have infinite input impedance or zero output impedance.
- **Cascading** of amplifiers, however, may be used to emphasize desirable characteristics.
  - first amplifier – high R_i, medium R_o
  - last amplifier – medium R_i, low R_o
  - aggregate – high R_i, low R_o

Example 1.3

$$\frac{v_{i1}}{v_s} = \frac{1\text{M}\Omega}{1\text{M}\Omega + 100\text{k}\Omega} = 0.909\text{V/V}$$

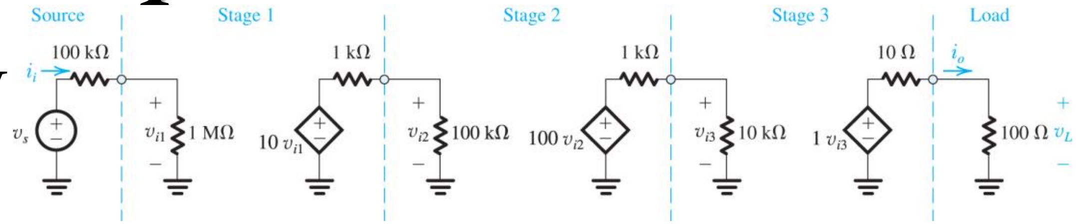


Figure 1.17 Three-stage amplifier for Example 1.3.

$$A_{v1} \equiv \frac{v_{i2}}{v_{i1}} = 10\frac{100\text{k}\Omega}{100\text{k}\Omega + 1\text{k}\Omega} = 9.9\text{V/V}$$

$$A_{v2} \equiv \frac{v_{i3}}{v_{i2}} = 100\frac{10\text{k}\Omega}{10\text{k}\Omega + 1\text{k}\Omega} = 90.9\text{V/V}$$

$$A_{v3} \equiv \frac{v_L}{v_{i3}} = 1\frac{100\Omega}{100\Omega + 10\Omega} = 0.909\text{V/V}$$

$$A_v \equiv \frac{v_L}{v_{i1}} = A_{v1}A_{v2}A_{v3} = 818\text{V/V}$$

=58.3dB

$$G_v \equiv \frac{v_L}{v_s} = \frac{v_{i1}}{v_s}A_v = 743.6\text{V/V}$$

=57.4dB

Bipolar junction transistor (BJT)

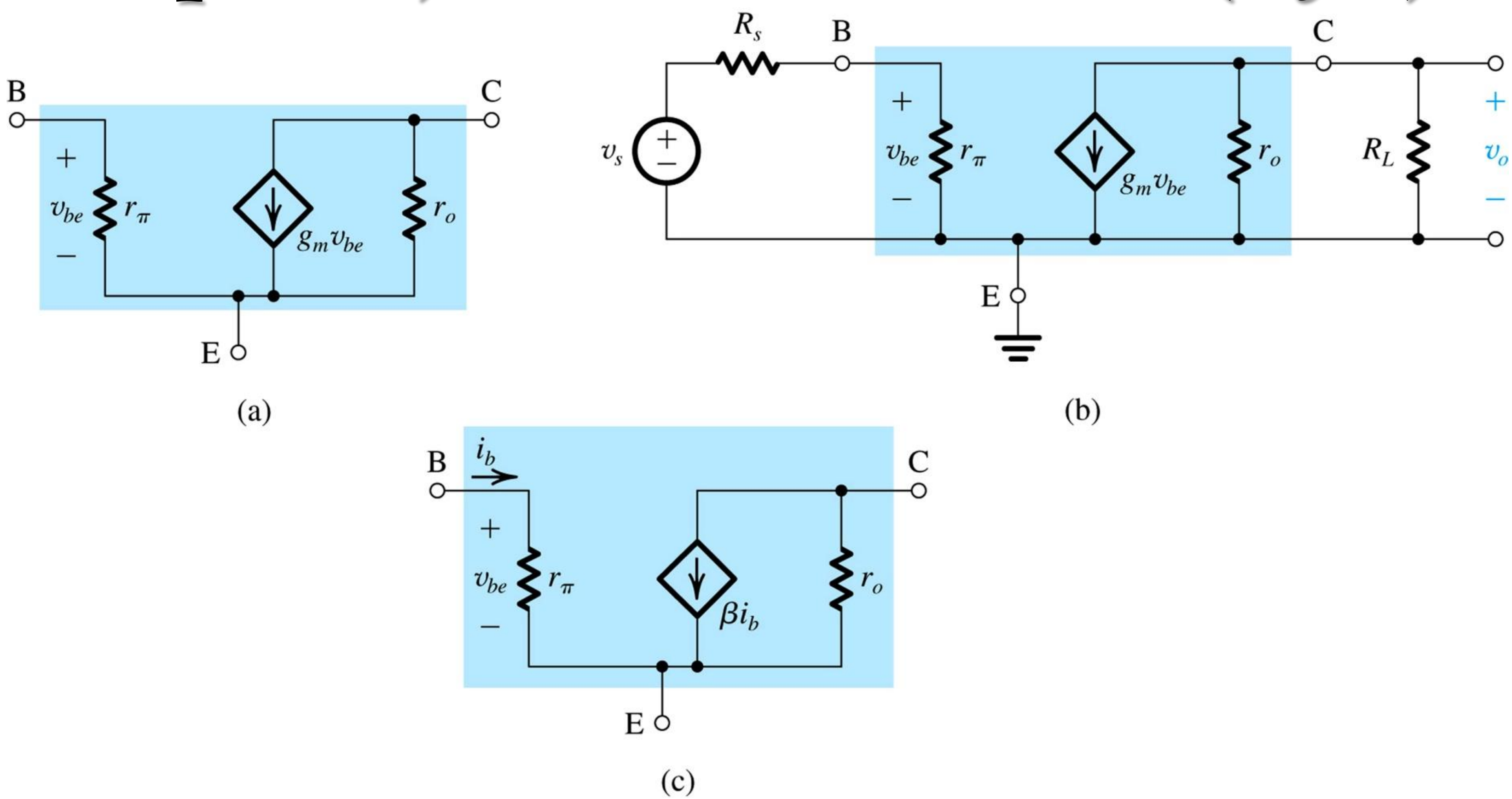
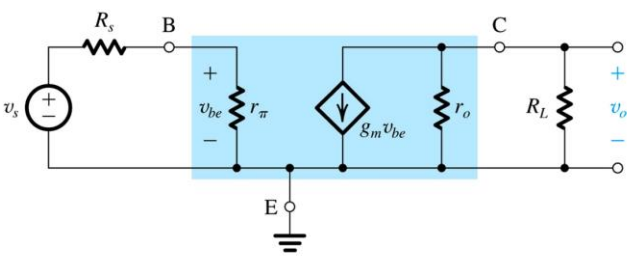


Figure 1.19 (a) Small-signal circuit model for a bipolar junction transistor (BJT). **(b)** The BJT connected as an amplifier with the emitter as a common terminal between input and output (called a common-emitter amplifier). **(c)** An alternative small-signal circuit model for the BJT.

Example 1.4

The bipolar junction transistor (BJT), which will be studied in Chapter 6, is a three-terminal device that when powered-up by a dc source (battery) and operated with small signals can be modeled by the linear circuit shown in Fig. 1.19(a). The three terminals are the base (B), the emitter (E), and the collector (C). The heart of the model is a transconductance amplifier represented by an input resistance between B and E (denoted r_π), a short-circuit transconductance g_m, and an output resistance r_o.

With the emitter used as a common terminal between input and output, Fig. 1.19(b) shows a transistor amplifier known as a common-emitter or grounded-emitter circuit. Derive an expression for the voltage gain v_o/v_s, and evaluate its magnitude for the case R_s = 5 kΩ, r_π = 2.5 kΩ, g_m = 40 mA/V, r_o = 100 kΩ, and R_L = 5 kΩ. What would the gain value be if the effect of r_o were neglected?



$$v_{be} = v_s \frac{r_\pi}{r_\pi + R_s} \qquad v_o = -g_m v_{be} \left(R_L \parallel r_o \right)$$

$$G_v \equiv \frac{v_o}{v_s} = -\frac{r_\pi}{r_\pi + R_s} g_m \left(R_L \parallel r_o \right) = -63.5\text{V/V} = 36.1\text{dB}$$

$$G_{v2} \equiv \frac{v_o}{v_s} = -\frac{r_\pi}{r_\pi + R_s} g_m R_L = -66.7\text{V/V} = 36.5\text{dB}$$

Homework #1

- Read Chapter 1
- Chapter 1 Problems: (due 2/13 at beginning of class)
  - 1.15*
  - 1.23
  - 1.24
  - 1.28
  - 1.30

* Answers in Appendix L

- Choose Lab Partners (2 to 4 members per team)
- Get Digilent Hardware and SIMetrix software

1.6 FREQUENCY RESPONSE OF AMPLIFIERS

Definitions

Transfer Function

- Relation between the input and output of a linear time-invariant system w.r.t. frequency.

Phase Response

- Relative phase of the output as a function of frequency.

Magnitude Response

- Magnitude of the gain of the system.

Amplifier Bandwidth

- The band of frequencies over which the gain of the amplifier is almost constant.

Measuring the frequency response of an amplifier

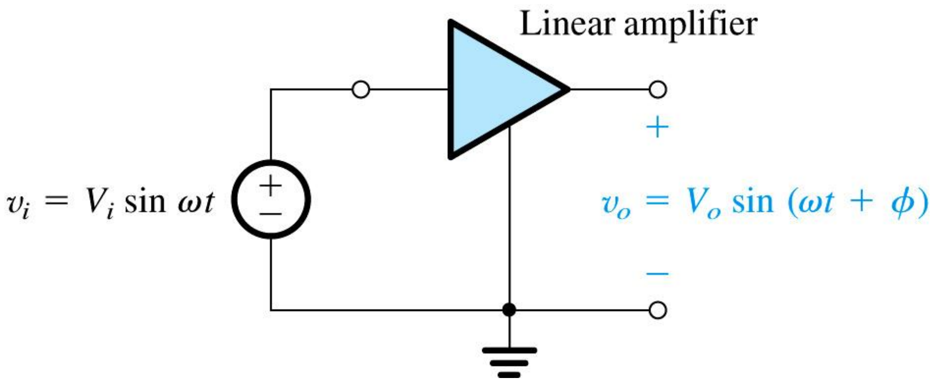


Figure 1.20 Measuring the frequency response of a linear amplifier: At the test frequency ω, the amplifier gain is characterized by its magnitude (V_o/V_i) and phase ϕ.

Magnitude response

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

Phase response

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

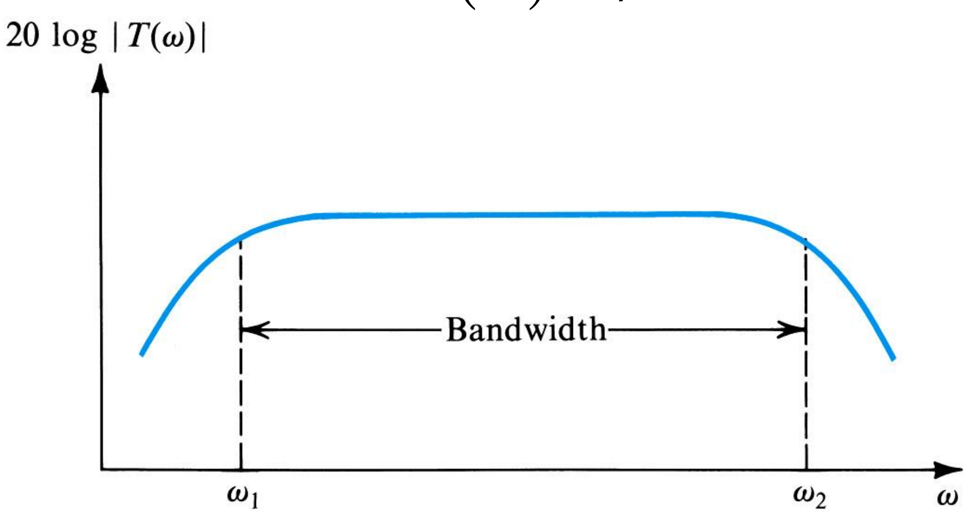


Figure 1.21 Typical magnitude response of an amplifier: $|T(\omega)|$ is the magnitude of the amplifier transfer function—that is, the ratio of the output $V_o(\omega)$ to the input $V_i(\omega)$.

Amplifier Bandwidth

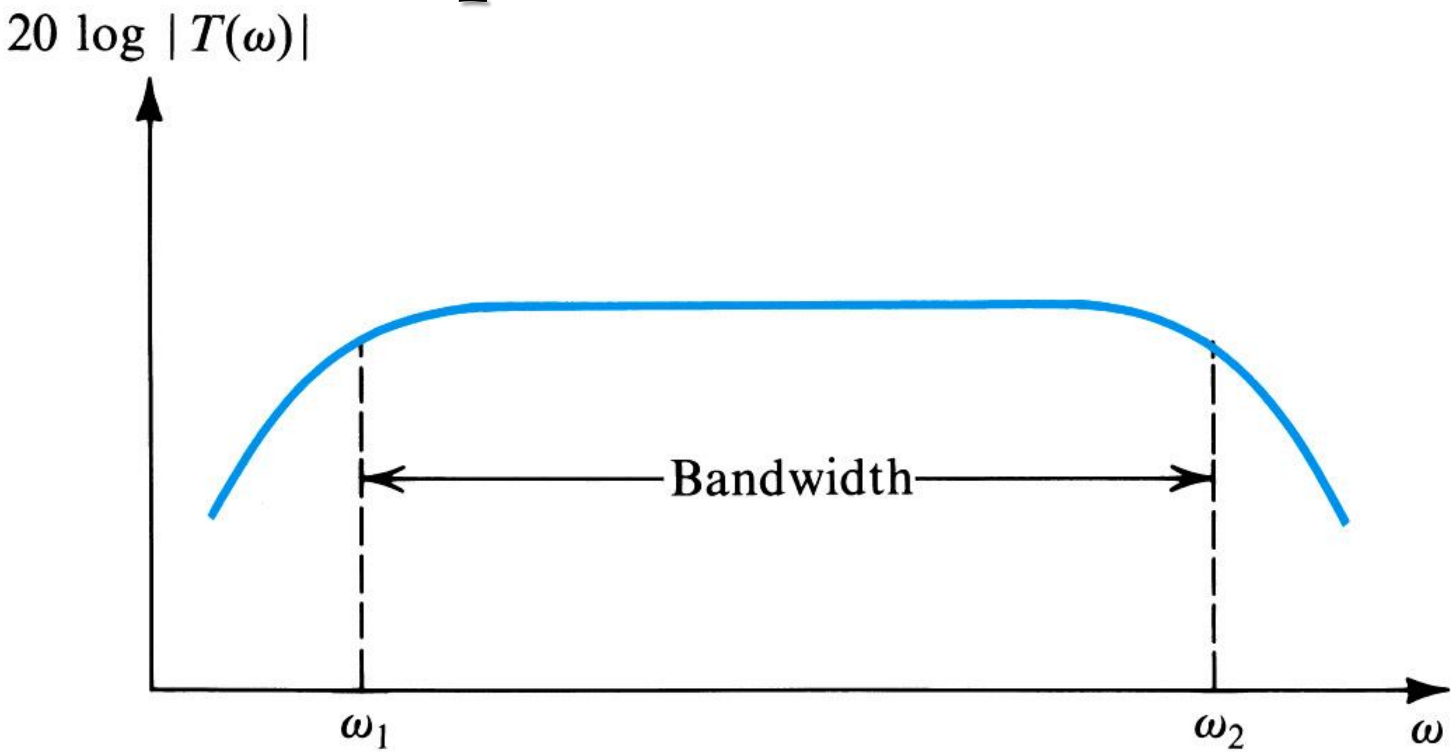


Figure 1.21 Typical magnitude response of an amplifier: $|T(\omega)|$ is the magnitude of the amplifier transfer function—that is, the ratio of the output $V_o(\omega)$ to the input $V_i(\omega)$.

Definitions

Complex Frequency Variable

- The variable *s* used to derive frequency response of circuits.

Single Time Constant (STC) Networks

- A network that can be reduced to one reactive and one resistive component.

Low Pass (LP) Circuit

- A circuit that passes frequencies below a cut-off, or “knee”, frequency.

High Pass (HP) Circuit

- A circuit that passes frequencies above a cut-off, or “knee”, frequency.

The *s* plane

The amplifier frequency response and stability are determined directly by its poles. Therefore we shall investigate the effect of feedback on the poles of the amplifier.

For an amplifier or any other system to be stable, its poles should lie in the left half of the *s* plane. Poles in the right half of the *s* plane give rise to growing oscillations. A pair of complex-conjugate poles on the *jw* axis gives rise to sustained sinusoidal oscillations. For an amplifier with a pole pair at $s = \sigma_0 \pm j\omega_n$

$$v(t) = e^{\sigma_0 t}\left[e^{+j\omega_n t} + e^{-j\omega_n t}\right] = 2e^{\sigma_0 t}\cos(\omega_n t)$$

Envelope function, σ_0 must be less than 0

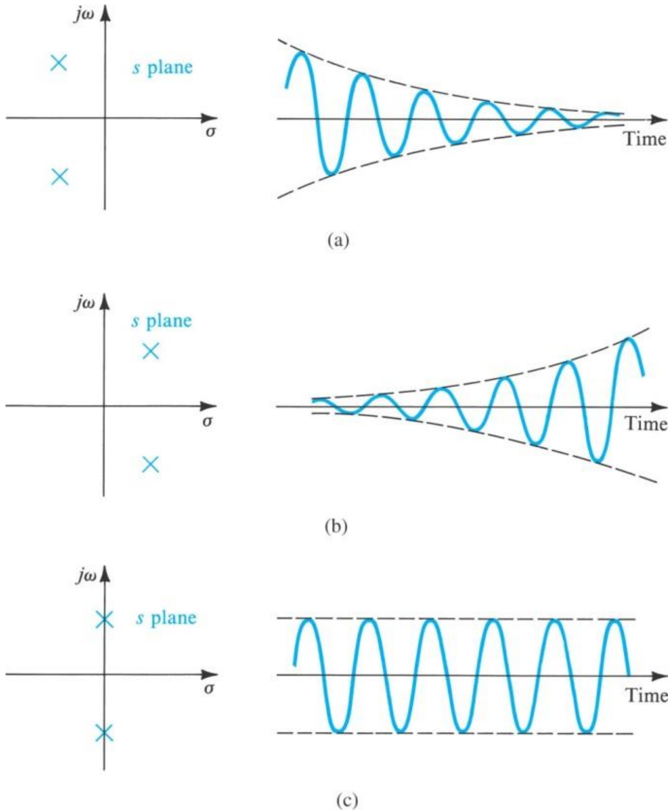


Figure 11.35 Relationship between pole location and transient response.

Single Time Constant (STC) Networks

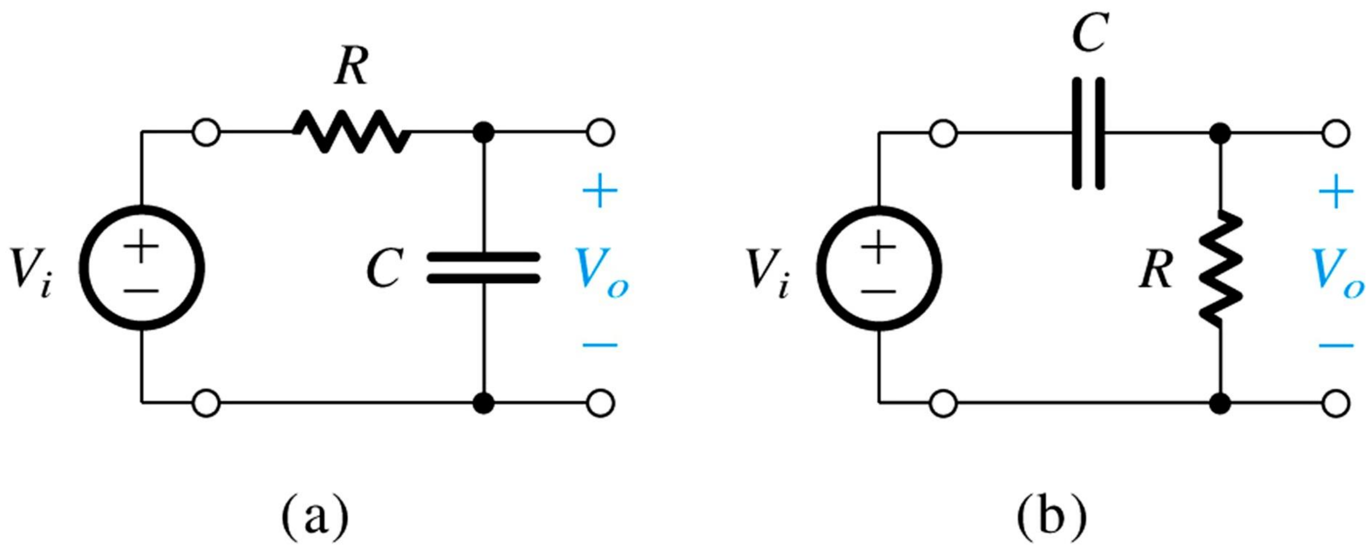


Figure 1.22 Two examples of STC networks: **(a)** a low-pass network and **(b)** a high-pass network.

$$X_C = \frac{1}{sC} \qquad X_L = sL$$

Impedance vs. Frequency

$$Z_R(\omega) = R$$

$$Z_C(\omega) = \frac{1}{j\omega C}$$

$$Z_L(\omega) = j\omega L$$

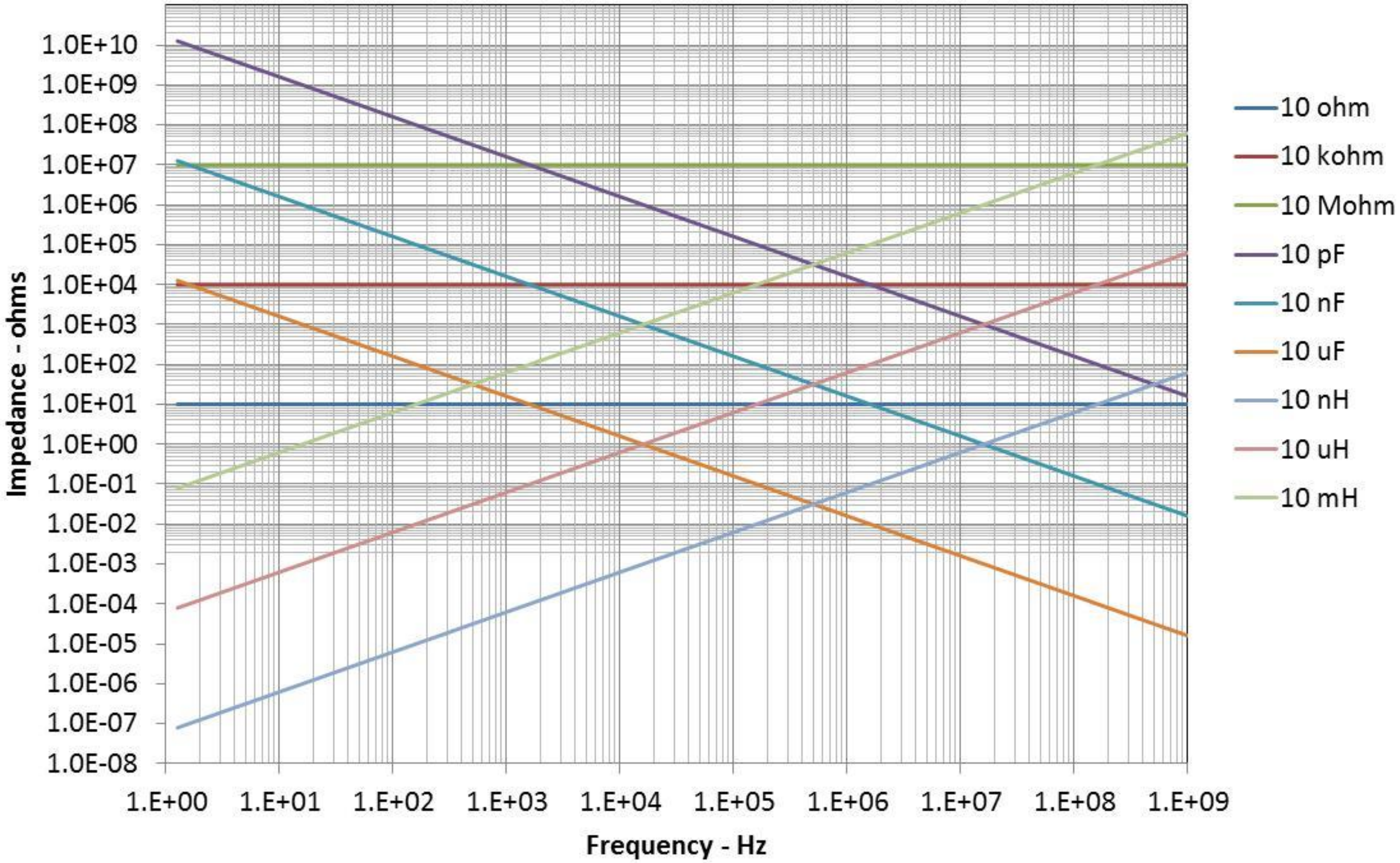


Table 1.2 Frequency Response of STC Networks

	Low-Pass (LP)	High-Pass (HP)
Transfer Function $T(s)$	$\dfrac{K}{1+\left({}^{s}/_{\omega_0}\right)}$	$\dfrac{Ks}{s+\omega_0}$
Transfer Function for physical frequencies $T(j\omega)$	$\dfrac{K}{1+j\left({}^{\omega}/_{\omega_0}\right)}$	$\dfrac{K}{1-j\left({}^{\omega_0}/_{\omega}\right)}$
Magnitude Response $\lvert T(j\omega)\rvert$	$\dfrac{\lvert K\rvert}{\sqrt{1+\left({}^{\omega}/_{\omega_0}\right)^2}}$	$\dfrac{\lvert K\rvert}{\sqrt{1+\left({}^{\omega_0}/_{\omega}\right)^2}}$
Phase Response $\angle T(j\omega)$	$-\tan^{-1}\left({}^{\omega}/_{\omega_o}\right)$	$\tan^{-1}\left({}^{\omega_o}/_{\omega}\right)$
Transmission at $\omega = 0$	K	0
Transmission at $\omega = \infty$	0	K
3-dB Frequency	$\omega_0 = {}^{1}/_{\tau}$, τ = time constant $\tau = CR$ or L/R	

Low-pass/High Pass Networks

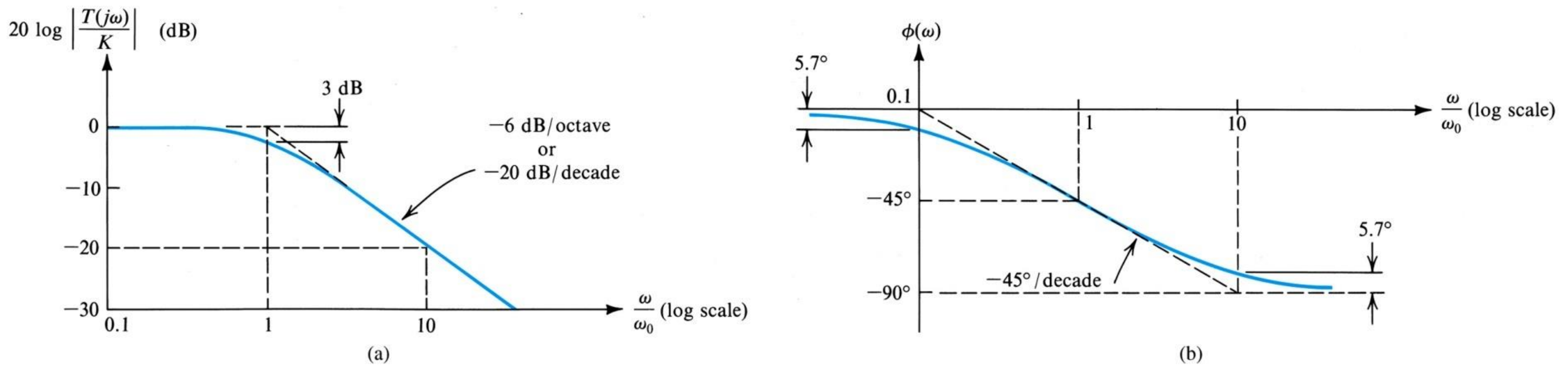


Figure 1.23 (a) Magnitude and **(b)** phase response of STC networks of the low-pass type.

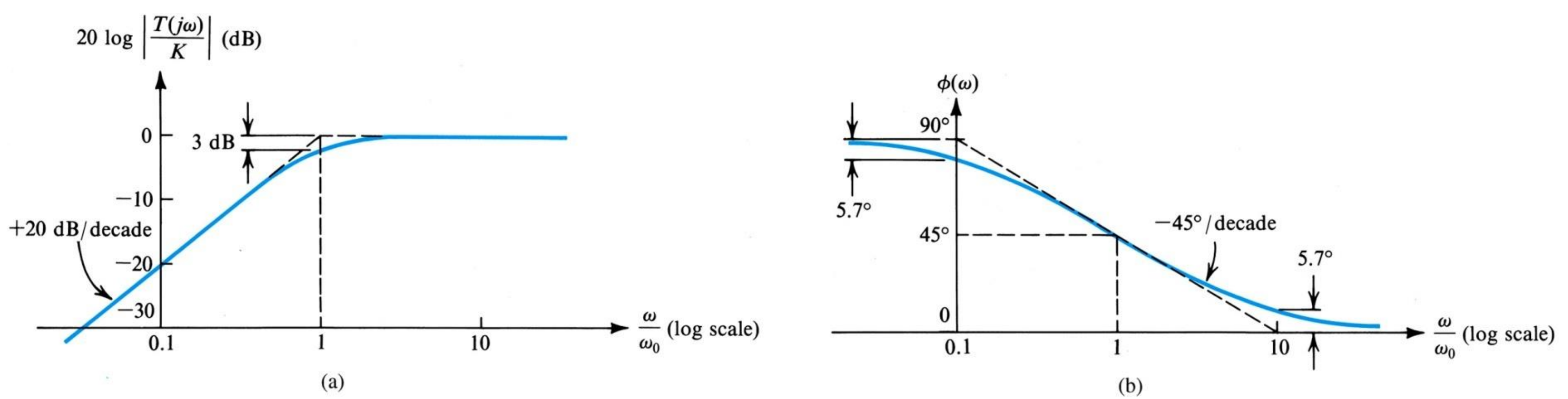


Figure 1.24 (a) Magnitude and **(b)** phase response of STC networks of the high-pass type.

Classification of Amplifiers Based on Frequency Response

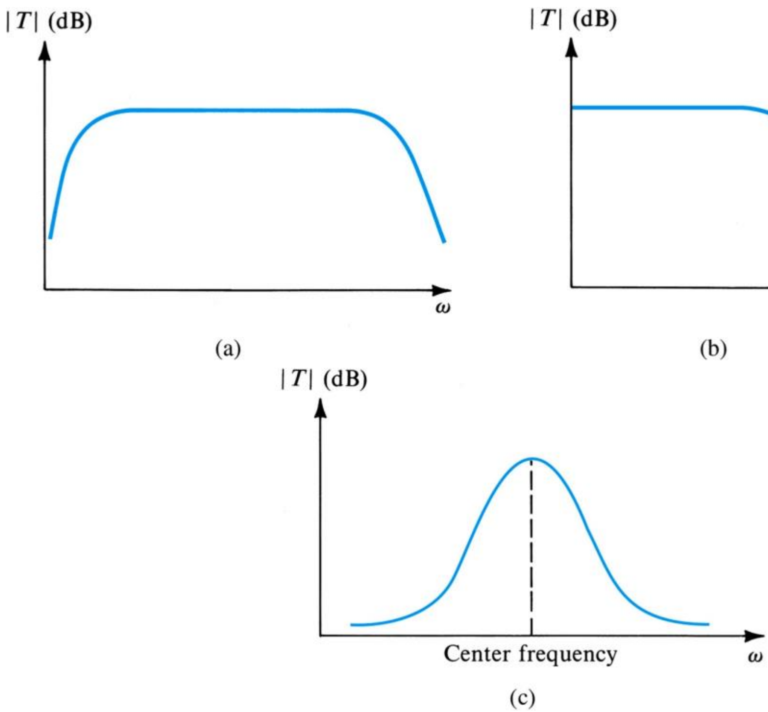


Figure 1.26 Frequency response for **(a)** a capacitively coupled amplifier, **(b)** a direct-coupled amplifier, and **(c)** a tuned or bandpass amplifier.

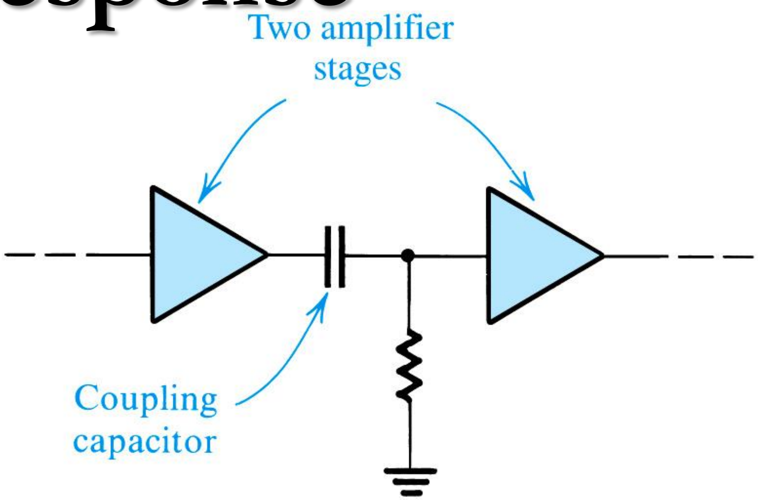


Figure 1.27 Use of a capacitor to couple amplifier stages.

internal capacitances – cause the falloff of gain at high frequencies

coupling capacitors – cause the falloff of gain at low frequencies

- are placed in between amplifier stages
- generally chosen to be large

Homework #2

- Finish reading Chapter 1
- Chapter 1 Problems: due 2/15 at the beginning of class
  - 1.39
  - 1.43
  - 1.45
  - 1.48*
  - 1.68*

* Answers in Appendix L

Ch 1 Summary

- An electrical signal source can be represented in either Thevenin form (a voltage source v_s in series with source resistance R_s) or the Norton form (a current source i_s in parallel with resistance R_s). The Thevenin voltage v_s is the open-circuit voltage between the source terminals. The Norton current i_s is equal to the short-circuit current between the source terminals. For the two representations to be equivalent, v_s and $R_s i_s$ must be equal.
- A signal can be represented either by its waveform vs time or as the sum of sinusoids. The latter representation is known as the frequency spectrum of the signal.
- The sine-wave signal is completely characterized by its peak value (or rms value which is the peak / $2^{1/2}$), frequency (ω in rad/s of f in Hz; $\omega = 2\pi f$ and $f = 1/T$, where T is the period is seconds), and phase with respect to an arbitrary reference time.

Ch 1 Summary Continued

- Analog signals have magnitudes that can assume any value. Electronic circuits that process analog signals are called analog circuits. Sampling the magnitude of an analog signal at discrete instants of time and representing each signal sample by a number results in a digital signal. Digital signals are processed by digital circuits.
- The simplest digital signals are obtained when the binary number system is used. An individual digital signal then assumes one of only two possible values: low and high (e.g. 0V and 5V) corresponding to logic 0 and logic 1.
- An analog-to-digital converter (ADC) provides at its output the digits of the binary number representing the analog signal sample applied to its input. The output digital signal can then be processed using digital circuits.
- A transfer characteristic, v_o vs. v_i, of a linear amplifier is a straight line with a slope equal to the voltage gain.

Ch 1 Summary Continued

- Amplifiers increase the signal power and thus require dc power supplies for their operation.
- The amplifier voltage gain can be expressed as a ratio A_v in V/V or in decibels, $20\mathbf{log}|A_v|$ in dB.
- Depending on the signal to be amplified (voltage or current) and on the desired form of output signal (voltage or current) there are four basic amplifier types: voltage, current, transconductance, and transresistance. A given amplifier may be modeled by any of these configurations, in which case their parameters are related by (1.14) through (1.16) in the text.
- The sinusoid is the only signal whose waveform is unchanged through a linear circuit. Sinusoidal signals are used to measure the frequency response of amplifiers.
- The transfer function $\mathbf{T}(s) = \mathbf{V}_o(s)/\mathbf{V}_i(s)$ of a voltage amplifier may be determined from circuit analysis. Substituting $s = j\omega$ gives $\mathbf{T}(j\omega)$ whose magnitude ($|\mathbf{T}(j\omega)|$ is the magnitude response and $\phi(\omega)$ is the phase response.

Ch 1 Summary Continued

- Amplifiers are classified according to the shape of their frequency response.
- Single-time-constant (STC) networks are those networks that are composed of, or may be reduced to, one reactive component (*L* or *C*) and one resistance. The time constant (τ) is L/R or RC.
- STC networks can be classified into two categories: low-pass (LP) and high-pass (HP). LP network pass dc and low-frequencies while attenuating high-frequencies. The opposite is true for HP.
- The gain of an LP (HP) STC circuit drops by 3dB below the zero-frequency (infinite-frequency) value at a frequency $\omega_0 = 1/\tau$. At high-frequencies (low-frequencies) the gain falls of at a rate of 6 dB/octave or 20 dB/decade.
  - Refer to Table 1.2. on page 34 and Figs. 1.23 and 1.24. Further details are provided in Appendix E.