Chapter 1

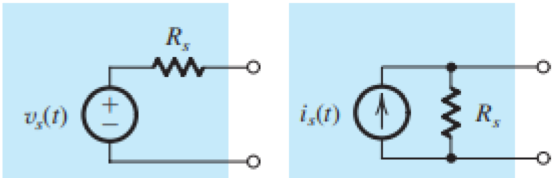
1. Signals

Signals contain information about a variety of things and activities in our physical world.

To extract required information from a set of signals, the observer (a human or a machine) invariably needs to process the signals in some predetermined manner. This signal processing is usually most conveniently performed by electronic systems.

The signal must first be converted into an electrical signal. This process is accomplished by devices known as transducers. For instance, the sound waves generated by a human can be converted into electrical signals by using a microphone, which is in effect a pressure transducer.

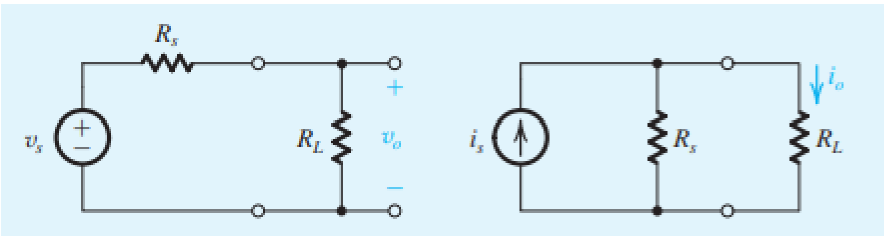
Assume that the signals of interest already exist in the electrical domain and represent them by one of the two equivalent forms:



Thevenin form is preferred when $\boldsymbol{R_s}$ is low. Norton form is preferred when $\boldsymbol{R_s}$ is high.

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

The output resistance of a signal source is an imperfection that limits the ability of the source to deliver its full signal strength to a load.



For the Thevenin-represented signal source:

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

For $v_o \cong v_s$, then $R_s \ll R_l$

For the Norton-represented signal source:

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

For $i_o \cong i_s$, then $R_s \gg R_l$

We note that although circuit designers cannot usually do much about the value of Rs, they may have to devise a circuit solution that minimizes or eliminates the loss of signal strength that results when the source is connected to the load.

A signal is a time-varying quantity. The information content of the signal is represented by the changes in its magnitude as time progresses.

2. Frequency Spectrum of Signals

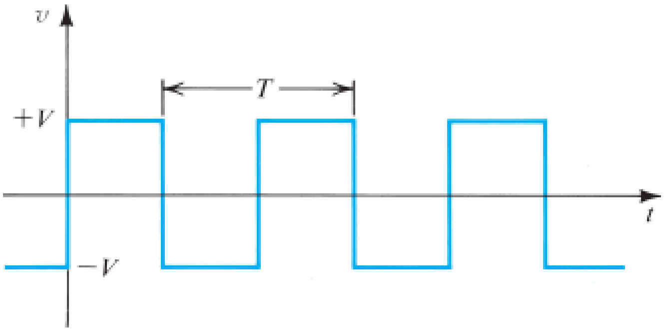
An extremely useful characterization of a signal is frequency spectrum. Such a description of signals is obtained through the mathematical tools of Fourier series and Fourier transform.

They provide the means for representing a voltage signal $v_s(t)$ or a current signal $i_s(t)$ as the sum of sine-wave signals of different frequencies and amplitudes.

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

The sine-wave signal is completely characterized by its peak value V_a, its frequency ω, and its phase with respect to an arbitrary reference time. It is common to express the amplitude of a sine-wave signal in terms of its root-mean-square (rms) value.

The Fourier series allows us to express a given periodic function of time as the sum of an infinite number of sinusoids whose frequencies are harmonically related.



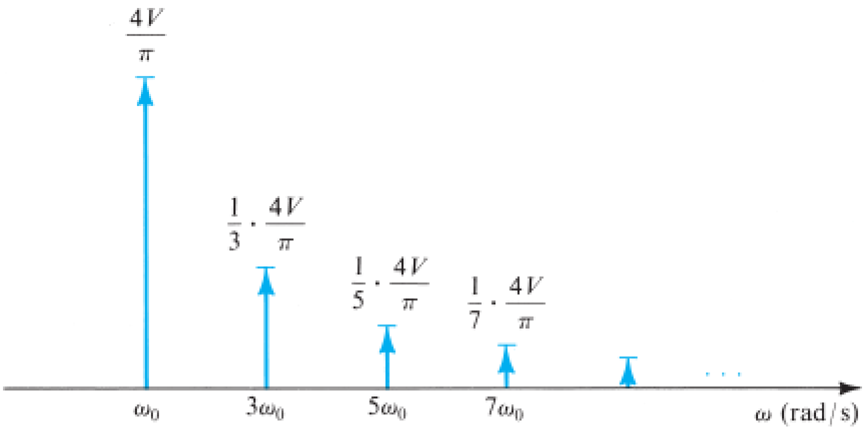
For instance, the symmetrical square-wave signal in this figure can be expressed as:

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

where V is the amplitude of the square wave and $\omega_0 = 2\pi/T$ is called the fundamental frequency.

Note that because the amplitudes of the harmonics progressively decrease, the infinite series can be truncated, with the truncated series providing an approximation to the square waveform.

The sinusoidal components in the series of above equation constitute the frequency spectrum of the square-wave signal. Such a spectrum can be graphically represented as in this figure.



The Fourier transform can be applied to a nonperiodic function of time and provides its frequency spectrum as a continuous function of frequency.

The spectrum of a nonperiodic signal contains in general all possible frequencies. Nevertheless, the essential parts of the spectra of practical signals are usually confined to relatively short segments of the frequency (ω) axis.

For instance, the spectrum of audible sounds such as speech and music extend from about 20 Hz to about 20 kHz (audio band).

A signal can be represented either by the manner in which its waveform varies with time (time-domain representation) or in terms of its frequency spectrum (frequency-domain representation).

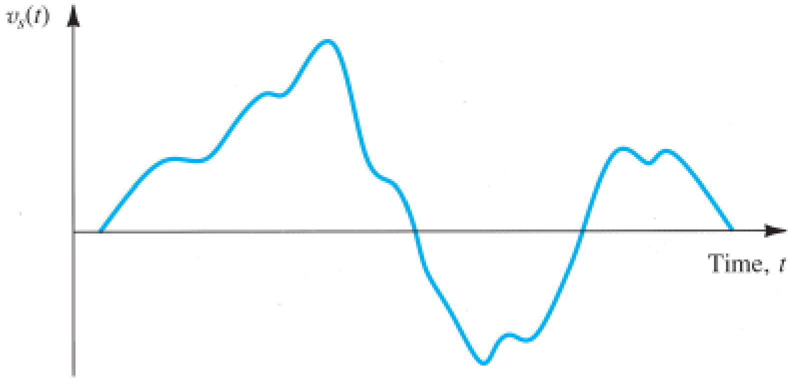
3. Analog and Digital Signals

The magnitude of an analog signal can take on any value; that is, the amplitude of an analog signal exhibits a continuous variation over its range of activity.

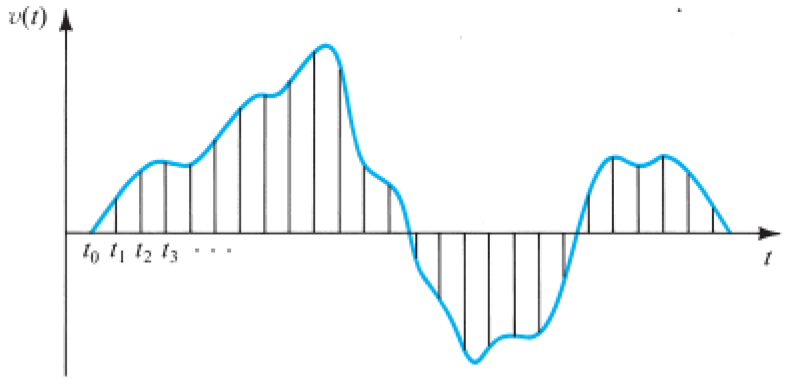
The vast majority of signals in the world around us are analog.

A sequence of numbers, each number representing the signal magnitude at an instant of time is called digital signal.

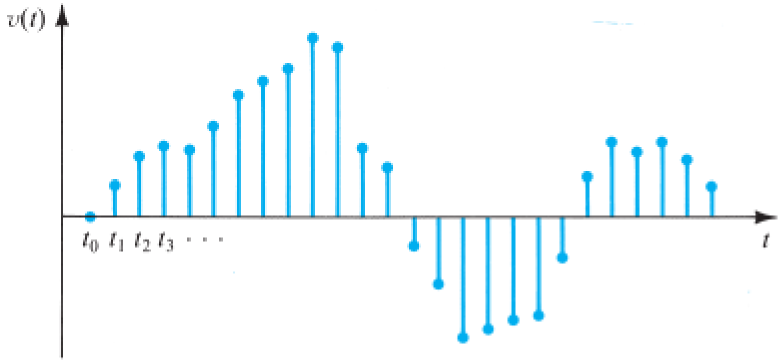
How signals can be converted from analog to digital form:



At equal intervals along the time axis, we have marked the time instants t0,t1,t2, and so on. At each of these time instants, the magnitude of the signal is measured, a process known as **sampling**.



The signal is defined only at the sampling instants (discrete-time signal)). However, since the magnitude of each sample can take any value in a continuous range, it is still an analog signal.



Represent the magnitude of each of the signal samples by a number having a finite number of digits, then the signal amplitude will no longer be continuous, it is said to be quantized, discretized, or digitized (**quantization**).

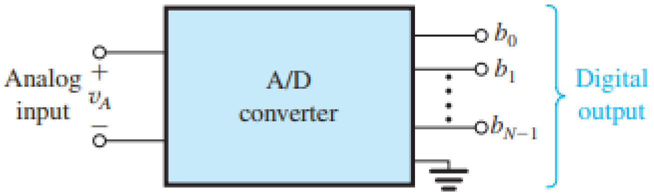
The choice of number system to represent the signal samples affects the type of digital signal produced and has a profound effect on the complexity of the digital circuits required to process the signals (**encoding**).

The binary number system is the simplest possible digital signals and circuits. Two possible values 1 and 0 (+5V and 0V) (high and low). If we use N binary digits (bits) to represent each sample of the analog signal, then the digitized sample value can be expressed as:

$$D = b_0 2^0 + b_1 2^1 + b_2 2^2 + \cdots + b_{N-1} 2^{N-1}$$

Increasing the number of bits reduces the quantization error and increases the resolution of analog-to-digital conversion.

A very important circuit building block of modern electronic systems: the analog-to-digital converter (A/D or ADC). The ADC accepts at its input the samples of an analog signal and provides for each input sample the corresponding N-bit digital representation.



4. Amplifiers

4.1. Signal Amplification

The need for amplification arises because transducers provide weak signals (in μV or mV). Such signals are too small for reliable processing, and processing is much easier if the signal magnitude is made larger.

Care must be exercised in the amplification of a signal, so that the information contained in the signal is not changed. We want the output signal of the amplifier to be an exact replica of that at the input, except of course for having larger magnitude. Any change in waveform is considered to be **distortion.**

An amplifier that preserves the details of the signal waveform is characterized by the relationship:

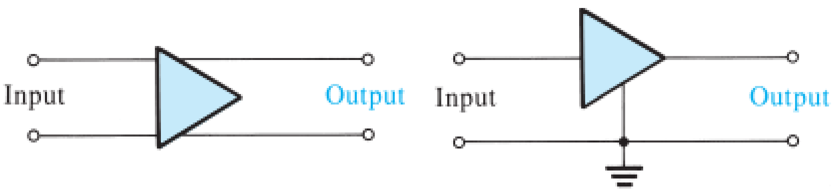
$$v_o(t) = Av_i(t)$$

- ➔ A is amplifier gain (constant representing the magnitude of the amplification)
- ➔ This equation is linear relationship; hence the amplifier it describes is a linear amplifier.
- ➔ If the equation contains higher powers of v_i then the amplifier is said to exhibit nonlinear distortion.

The amplifiers discussed so far are primarily intended to operate on very small input signals. Their purpose is to make the signal magnitude larger, and therefore they are thought of as voltage amplifiers.

4.2. Amplifier Circuit Symbol

The signal amplifier is obviously a two-port circuit.



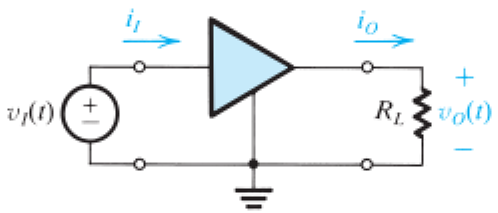
4.3. Voltage Gain

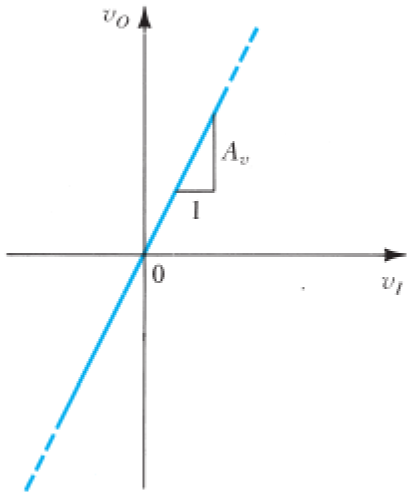
A linear amplifier accepts an input signal $v_i(t)$ and provides at the output, across a load resistance R_L, an output signal $v_o(t)$ that is a magnified replica of $v_i(t)$.

The voltage gain of the amplifier is defined by:

$$A_v = \frac{v_o}{v_i}$$

The transfer characteristic of a linear amplifier shows that if we apply to the input of this amplifier a sinusoidal voltage of amplitude $\hat{V}$, we obtain at the output a sinusoid of amplitude $A_v\hat{V}$.





4.4. Power Gain and Current Gain

An amplifier increases the signal power, an important feature that distinguishes an amplifier from a transformer.

The power gain of the amplifier is defined as:

$$A_p = \frac{P_L}{P_i} = \frac{v_o i_o}{v_i i_i}$$

The current gain of the amplifier is defined as:

$$A_i = \frac{i_o}{i_i}$$

And we can notice that:

$$A_p = A_v A_i$$

4.5. Expressing Gain in Decibels

The amplifier gains defined above are ratios of similarly dimensioned quantities. Thus they will be expressed as dimensionless numbers.

$$\text{Voltage gain in decibels} = 20\log|A_v|$$

$$\text{Current gain in decibels} = 20\log|A_i|$$

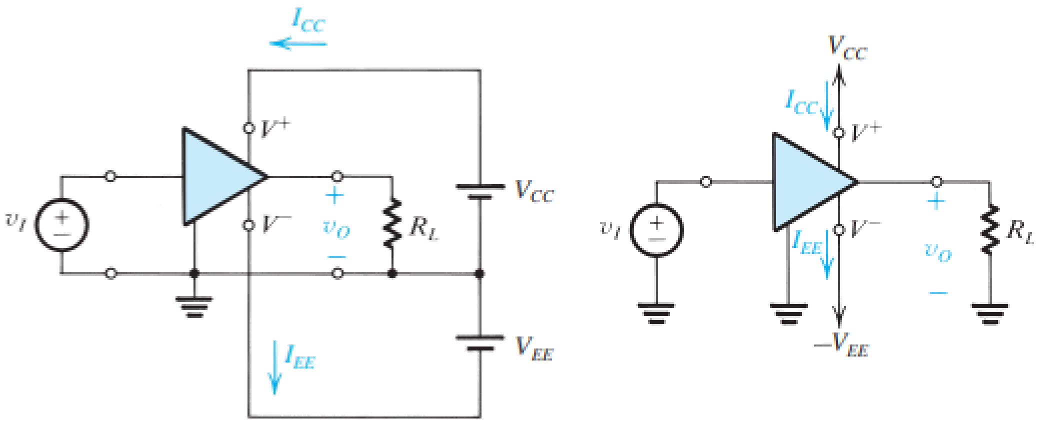
$$\text{power gain in decibels} = 10\log A_p$$

The absolute values of the voltage and current gains are used because in some cases Av or Ai will be a negative number. A negative gain Av simply means that there is a 180° phase difference between input and output signals; it does not imply that the amplifier is attenuating the signal.

4.6. The Amplifier Power Supplies

Since the power delivered to the load is greater than the power drawn from the signal source, the question arises as to the source of this additional power.

The answer is that amplifiers need dc power supplies for their operation. These dc sources supply the extra power delivered to the load as well as any power that might be dissipated in the internal circuit.



This figure shows an amplifier that requires two dc sources:

- ➔ one positive of value VCC.
- ➔ one negative of value VEE.

The amplifier has two terminals, labelled V^+ and V^-, for connection to the dc supplies.

The dc power delivered to the amplifier is:

$$P_{dc} = V_{CC}I_{CC} + V_{EE}I_{EE}$$

If the power dissipated in the amplifier circuit is denoted $P_{\text{dissipated}}$, the power-balance equation for the amplifier can be written as:

$$P_i + P_{dc} = P_L + P_{\text{dissipated}}$$

The amplifier power efficiency is defined as:

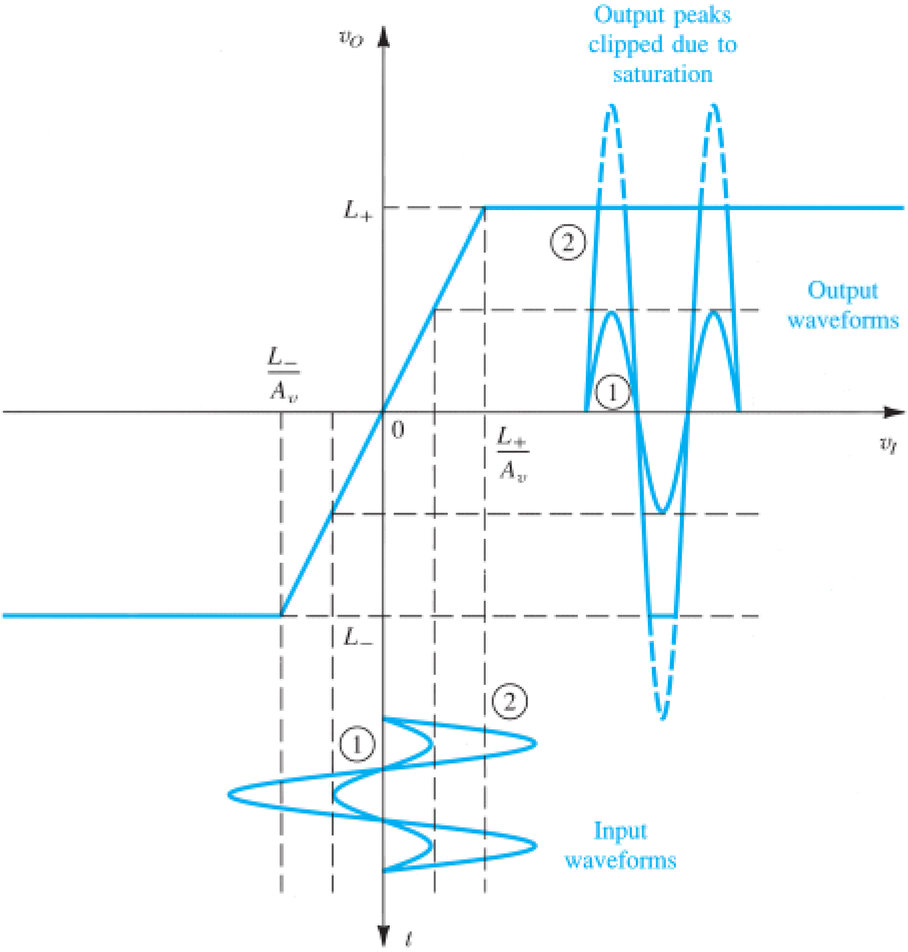
$$\eta = \frac{P_L}{P_{dc}} \times 100$$

The power efficiency is an important performance parameter for amplifiers that handle large amounts of power.

4.7. Amplifier Saturation

Practically, the amplifier transfer characteristic remains linear over only a limited range of input and output voltages.

The output voltage cannot exceed a specified positive limit and cannot decrease below a specified negative limit.



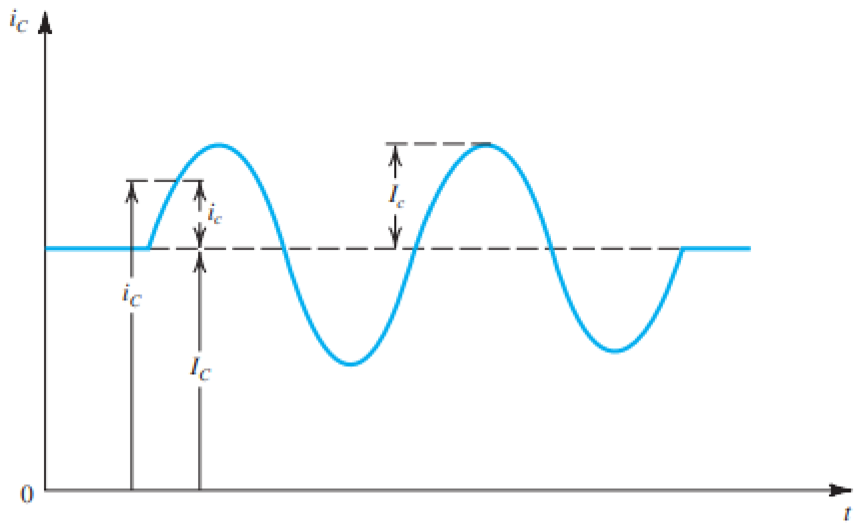
In order to avoid distorting the output signal waveform, the input signal swing must be kept within the linear range of operation.

$$\frac{L_-}{A_v} \leq v_i \leq \frac{L_+}{A_v}$$

The figure shows two input waveforms and the corresponding output waveforms, the peaks of the larger waveform have been clipped off because of amplifier saturation.

4.8. Symbol Convention

This figure shows the symbol convention:



- ➔ $I_C \rightarrow DC\ current$
- ➔ $i_c \rightarrow instantenious\ current$

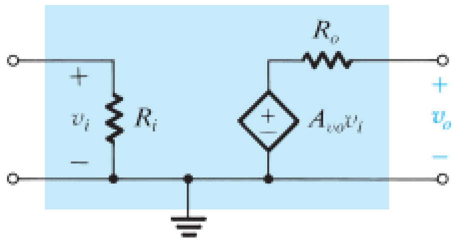
- ➔ $I_c \rightarrow peak\ amplitude\ of\ i_c(t)$
- ➔ $i_C \rightarrow sum\ of\ DC\ current\ and\ instantenious\ current$

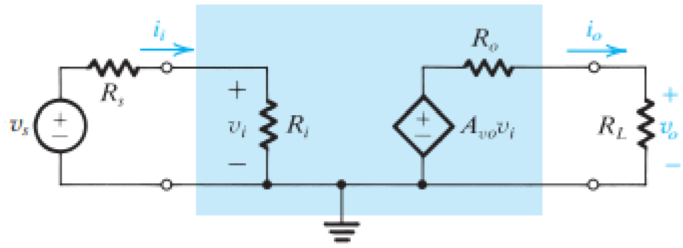
5. Circuit Models for Amplifiers

In order to be able to apply the resulting amplifier circuit as a building block in a system, one must be able to characterize, or model, its terminal behavior.

5.1. Voltage Amplifiers

Figure shows a circuit model for the voltage amplifier.





@ Output:

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

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

- ➔ In order not to lose gain in coupling the amplifier output to a load, the output resistance R_o should be much smaller than the load resistance R_L.
(for a given R_L one must design the amplifier so that its R_o is much smaller than R_L)
- ➔ An ideal voltage amplifier is one with $R_o = 0$.
- ➔ If $R_L = \infty$ then $A_v = A_{vo}$. Thus, A_{vo} is called open-circuit voltage gain.

@ Input:

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

- ➔ In order not to lose a significant portion of the input signal in coupling the signal source to the amplifier input, the amplifier must be designed to have an input resistance R_i much greater than the resistance of the signal source R_s.
- ➔ An ideal voltage amplifier is one with $R_i = \infty$.
- ➔ For ideal case, $A_i = \infty$ and $A_P = \infty$.

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

5.2. Cascaded Amplifiers

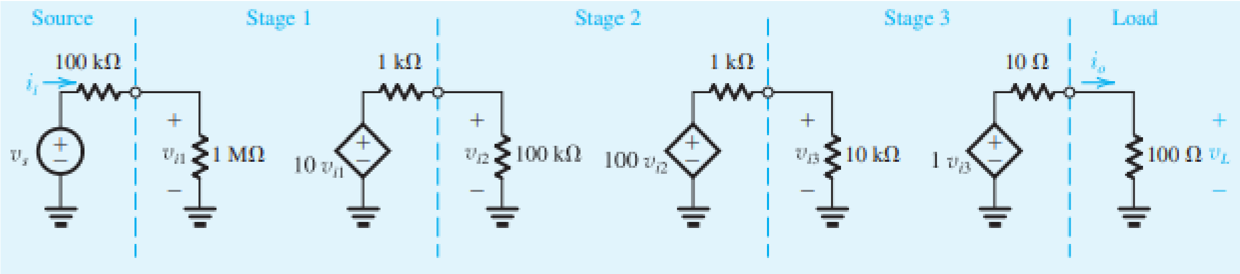
To meet given amplifier specifications, we often need to design the amplifier as a cascade of two or more stages. The stages are usually not identical; rather, each is designed to serve a specific purpose.

- ➔ In order to provide the overall amplifier with a large input resistance, the first stage is usually required to have a large input resistance.
- ➔ In order to equip the overall amplifier with a low output resistance, the final stage in the cascade is usually designed to have a low output resistance.

- Example

An amplifier composed of a cascade of three stages. The amplifier is fed by a signal source with a source resistance of 100 kΩ and delivers its output into a load resistance of 100 Ω.

The first stage has a relatively high input resistance and a modest gain factor of 10.
The second stage has a higher gain factor but lower input resistance.
Finally, the last, or output, stage has unity gain but a low output resistance.



Evaluate:

- The overall voltage gain.
- The current gain.
- The power gain.

Solution:

Source:

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

Stage 1:

$$v_{i2} = 10 v_{i1} \frac{100\ \text{k}\Omega}{1\ \text{k}\Omega + 100\ \text{k}\Omega}$$

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

Stage 2:

$$v_{i3} = 100 v_{i2} \frac{10\ \text{k}\Omega}{1\ \text{k}\Omega + 10\ \text{k}\Omega}$$

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

Stage 3:

$$v_L = 1 v_{i3} \frac{100\ \Omega}{10\ \Omega + 100\ \Omega}$$

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

Total gain:

$$A_v = \frac{v_L}{v_{i1}} = A_{v1} A_{v2} A_{v3} = 818$$

- Overall gain

$$\frac{v_L}{v_s} = \frac{v_L}{v_{i1}} \times \frac{v_{i1}}{v_s} = A_v \frac{v_{i1}}{v_s} = 818 \times 0.909 = 743.562$$
$$= 20 \log 743.562 = 57.43\ \text{dB}$$

- Current gain

$$A_i = \frac{i_o}{i_i} = \frac{\frac{v_L}{100}\Omega}{\frac{v_{i1}}{1}\text{M}\Omega} = A_v \times 10^4 = 8.18 \times 10^6$$

$$= 20 \log 8.18 \times 10^6 = 138.255 \text{ dB}$$

- Power gain

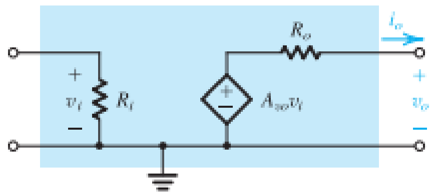
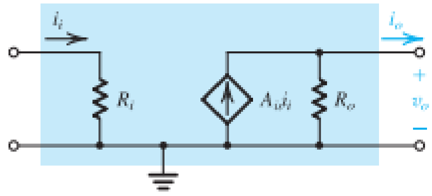
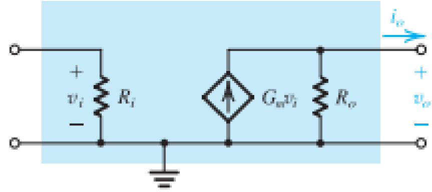
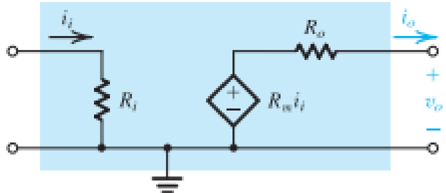
$$A_P = \frac{P_L}{P_i} = \frac{v_L \times i_o}{v_{i1} \times i_i} = A_v A_i = 6.69 \times 10^9$$

$$= 10 \log 6.69 \times 10^9 = 98.255 \text{ dB}$$

5.3. Other Amplifier Types

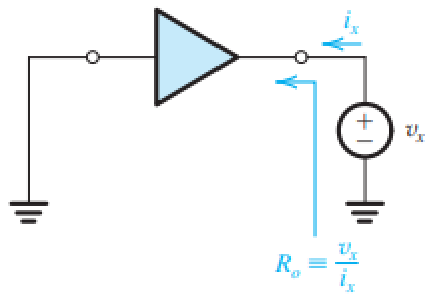
In the design of an electronic system, the signal of interest. The voltage amplifier considered above is just one of four possible amplifier types. The other three are the current amplifier, the transconductance amplifier, and the transresistance amplifier.

5.4. Relationships between the Four Amplifier Models

Type	Circuit Model	Gain Parameter	Ideal Characteristics
Voltage Amplifier		Open-Circuit Voltage Gain $A_{vo} = \left.\frac{v_o}{v_i}\right\rvert_{i_o=0}$	$R_i = \infty$ $R_o = 0$
Current Amplifier		Short-Circuit Current Gain $A_{io} = \left.\frac{i_o}{i_i}\right\rvert_{v_o=0}$	$R_i = 0$ $R_o = \infty$
Transconductance Amplifier		Short-Circuit Transconductance $G_m = \left.\frac{i_o}{v_i}\right\rvert_{v_o=0}$	$R_i = \infty$ $R_o = \infty$
Transresistance Amplifier		Open-Circuit Transresistance $R_m = \left.\frac{v_o}{i_i}\right\rvert_{i_o=0}$	$R_i = 0$ $R_o = 0$

5.5. Determining R_i and R_o

- ➔ The input resistance R_i of the amplifier can be determined by applying an input voltage v_i and measuring (or calculating) the input current i_i; that is, $R_i = v_i / i_i$.
- ➔ The output resistance can be found by eliminating the input signal source (then i_i and v_i will both be zero) and applying a voltage signal v_x to the output of the amplifier. If we denote the current drawn from v_x into the output terminals as i_x then $R_o = v_x / i_x$.

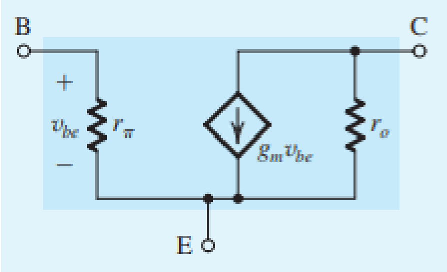


5.6. Unilateral Models

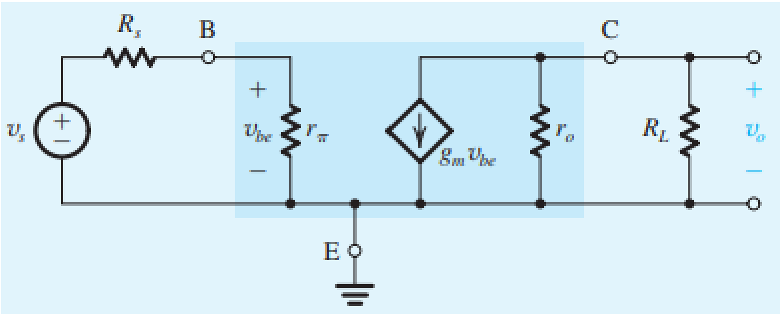
The amplifier models considered above are unilateral; that is, signal flow is unidirectional, from input to output. Most real amplifiers show some reverse transmission, which is usually undesirable but must nonetheless be modeled.

- Example

The bipolar junction transistor (BJT) can be modeled by the linear circuit (small-signal model):

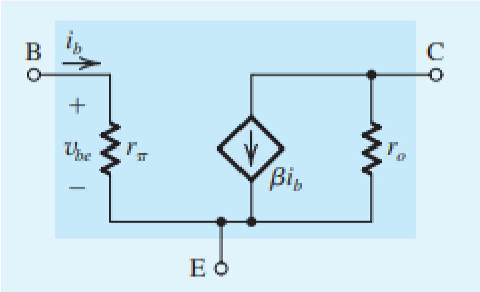


With the emitter used as a common terminal between input and output, figure shows a transistor amplifier known as a common emitter:



➔ Derive an expression for the voltage gainv_o/v_s, and evaluate its magnitude for the case $R_s = 5\text{ k}\Omega$, $r_\pi = 2.5\text{ k}\Omega$, $g_m = 40\text{ mA/V}$, $r_o = 100\text{ k}\Omega$, and $R_L = 5\text{ k}\Omega$ k. What would the gain value be if the effect of r_o were neglected?

An alternative model for the transistor in which a current amplifier rather than a transconductance amplifier is utilized is shown in this figure:



➔ What must the short-circuit current gain β be? Give both an expression and a value.

Solution:

$$v_{be} = v_s \frac{r_\pi}{r_\pi + R_s}$$

$$v_o = -g_m v_{bo}(R_L \parallel r_o)$$

$$\frac{v_o}{v_s} = -g_m \frac{r_\pi}{r_\pi + R_s}(R_L \parallel r_o) = -40 \times \frac{2.5}{2.5+5}(5 \parallel 100) = -63.49$$

If the effect of r_o were neglected:

$$\frac{v_o}{v_s} = -g_m \frac{r_\pi}{r_\pi + R_s}(R_L) = -40 \times \frac{2.5}{2.5+5}(5) = -66.67$$

which is quite close to the value obtained including r_o. This is not surprising, since $r_o \gg R_L$.

$$\beta i_b = g_m v_{be}$$

$$i_b = \frac{v_{be}}{r_\pi}$$

$$\beta = g_m r_\pi = 40 \times 2.5 = 100$$

6. Frequency Response of Amplifiers

The input signal to an amplifier can always be expressed as the sum of sinusoidal signals. It follows that an important characterization of an amplifier is in terms of its response to input sinusoids of different frequencies.

6.1. Measuring the Amplifier Frequency Response

Whenever a sine-wave signal is applied to a linear circuit, the resulting output is sinusoidal with the same frequency as the input. However, that the output sinusoid will in general have a different amplitude and will be shifted in phase relative to the input.

- ➔ The ratio of the amplitude of the output sinusoid (V_o) to the amplitude of the input sinusoid (V_i) is the magnitude of the amplifier gain at the test frequency ω.
- ➔ The angle ϕ is the phase of the amplifier transmission at the test frequency ω.

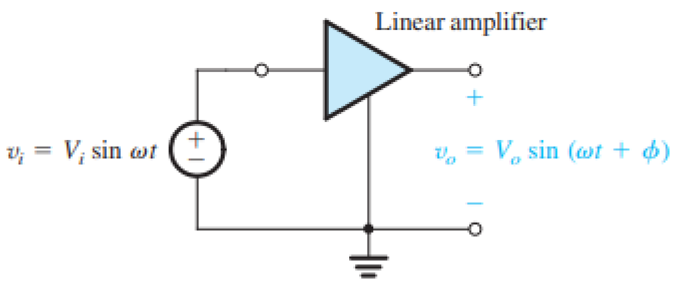
Then, transfer function can be denoted by:

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

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

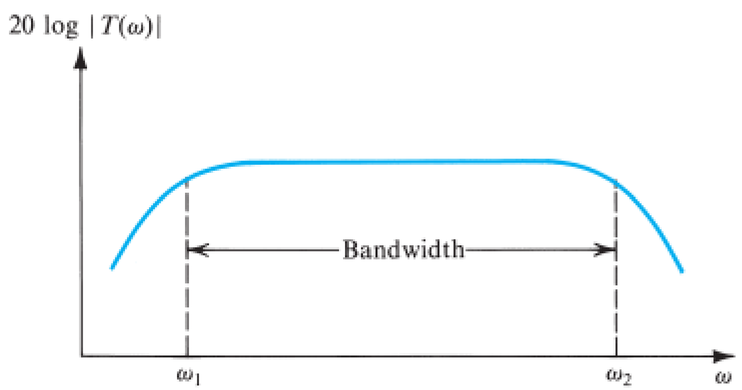
To obtain the complete frequency response of the amplifier we simply change the frequency of the input sinusoid and measure the new value for |T| and ∠T and can be plotted.

These two plots together constitute the frequency response of the amplifier; the first is known as the magnitude response (expressed in dB) and the second is the phase response.



6.2. Amplifier Bandwidth

Figure below shows the magnitude response of an amplifier. It indicates that the gain is almost constant over a wide frequency range, roughly between ω1 and ω2. Signals whose frequencies are below ω1 or above ω2 will experience lower gain.



The band of frequencies over which the gain of the amplifier is almost constant, is called Amplifier Bandwidth.

Normally the amplifier is designed so that its bandwidth coincides with the spectrum of the signals it is required to amplify. Otherwise the signal spectrum will be distorted.

6.3. Evaluating the Frequency Response of Amplifiers

To evaluate the frequency response of an amplifier, one has to analyse the amplifier equivalent circuit model, taking into account all reactive components. Thus in a frequency-domain analysis we deal with impedances and/or admittances.

The result of the analysis is the amplifier transfer function T(ω):

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

T(ω) is generally a complex function whose magnitude |T(ω)| gives the magnitude response of the amplifier. The phase of T(ω) gives the phase response of the amplifier.

The algebraic manipulations can be considerably simplified by using the complex frequency variable s:

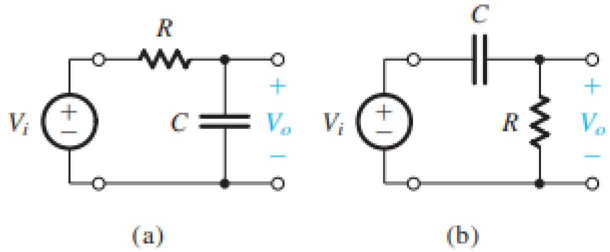
$$T(s) = \frac{V_o(s)}{V_i(s)}$$

6.4. Single-Time-Constant Networks

An STC network is one that is composed of, or can be reduced to, one reactive component (inductance or capacitance) and one resistance.

- ➔ An STC network formed of an inductance L and a resistance R has a time constant τ = L/R.
- ➔ An STC network formed of an inductance C and a resistance R has a time constant τ = CR.

Most STC networks can be classified into two categories, low pass (LP) and high pass (HP).



Observe that the transfer function of each of these two circuits can be expressed as a voltage-divider ratio, with the divider composed of a resistor and a capacitor.

Now, recalling how the impedance of a capacitor varies with frequency (Z = 1/jωC):

- ➔ In circuit (a), $T(\omega) = \frac{V_O(\omega)}{V_i(\omega)}$ will decrease with frequency and approach zero as ω approaches ∞. Thus, the circuit of Fig. (a) acts as a low-pass filter ; it passes low-frequency, sine-wave inputs with little or no attenuation (at ω = 0, the transmission is unity) and attenuates high-frequency input sinusoids.
- ➔ In circuit (b), $T(\omega) = \frac{V_O(\omega)}{V_i(\omega)}$ will increase with frequency and approach unity as ω approaches∞. Thus, the circuit of Fig. (a) acts as a High-pass filter

	Low-Pass (LP)	High-Pass (HP)
Transfer Function $T(s)$	$\frac{K}{1+(s/\omega_0)}$	$\frac{Ks}{s+\omega_0}$
Transfer Function (for physical frequencies) $T(j\omega)$	$\frac{K}{1+j(\omega/\omega_0)}$	$\frac{K}{1-j(\omega_0/\omega)}$
Magnitude Response $\|T(j\omega)\|$	$\frac{\|K\|}{\sqrt{1+(\omega/\omega_0)^2}}$	$\frac{\|K\|}{\sqrt{1+(\omega_0/\omega)^2}}$
Phase Response $\angle T(j\omega)$	$-\tan^{-1}(\omega/\omega_0)$	$\tan^{-1}(\omega_0/\omega)$
Transmission at $\omega = 0$ (dc)	K	0
Transmission at $\omega = \infty$	0	K
3-dB Frequency	$\omega_0 = 1/\tau$; $\tau \equiv$ time constant $\tau = CR$ or L/R	
Bode Plots	in Fig. 1.23	in Fig. 1.24