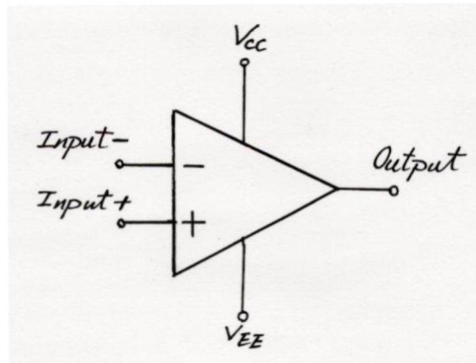
Lecture



Introduction to Operational Amplifiers

FIGURE 1.1 Progression from vacuum tubes to microelectronics

Date	Degree of Integration	Number of Components per Chip
1950s	Discrete components	1 to 2
1960s	Small-scale integration (SSI)	Fewer than 10^2
1966	Medium-scale integration (MSI)	From 10^2 to 10^3
1969	Large-scale integration (LSI)	From 10^3 to 10^4
1975	Very-large-scale integration (VLSI)	From 10^4 to 10^9
1990s	Ultra-large-scale integration (ULSI)	More than 10^9

Sensors

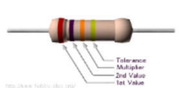
There are many types of sensors, including the following:

- Thermistors and thermocouples to measure temperature
- Phototransistors and photodiodes to measure light
- Strain gauges and piezoelectric materials to measure force
- Potentiometers, inductive sensors, and absolute position encoders to measure displacement
- Tachogenerators, accelerometers, and Doppler effect sensors to measure motion
- Microphones to measure sound
- Anemometer to measure the wind speed

Actuators

Actuators produce a nonelectrical output from an electrical signal. There are many types of actuators including the following:

- Resistive heaters to produce heat
- Light-emitting diodes (LEDs) and light dimmers to control the amount of light
- Solenoids to produce force



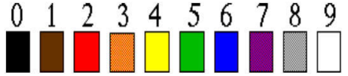
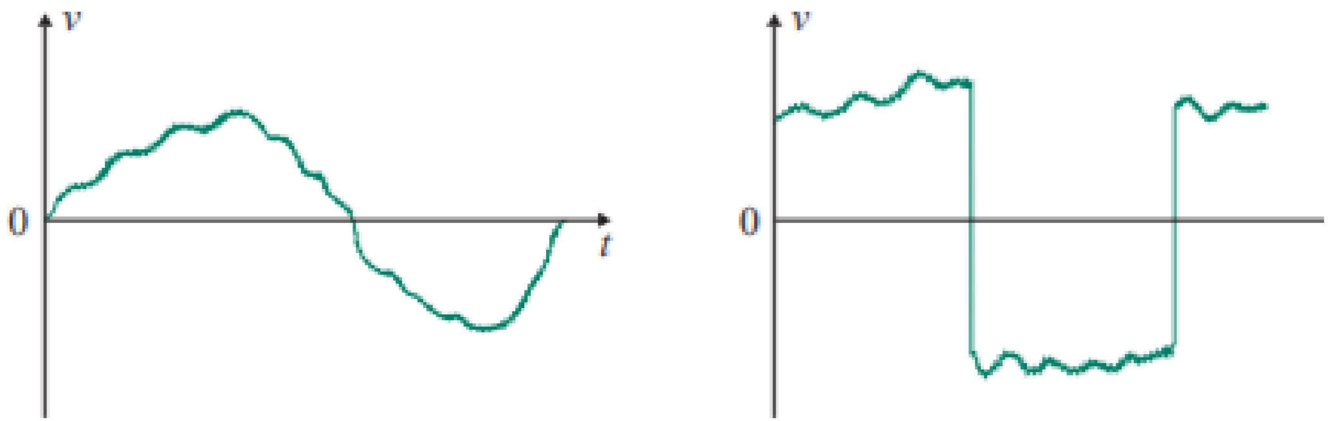


TABLE 1.2 Definition of symbols and subscripts

Definition	Quantity	Subscript	Example
DC value of the signal	Uppercase	Uppercase	V_D
AC value of the signal	Lowercase	Lowercase	v_d
Total instantaneous value of the signal (DC and AC)	Lowercase	Uppercase	v_D
Complex variable, phasor, or rms value of the signal	Uppercase	Lowercase	V_d

Types of noise:



(a) Analog signal plus noise **(b) Digital signal plus noise**

Types of distortion:

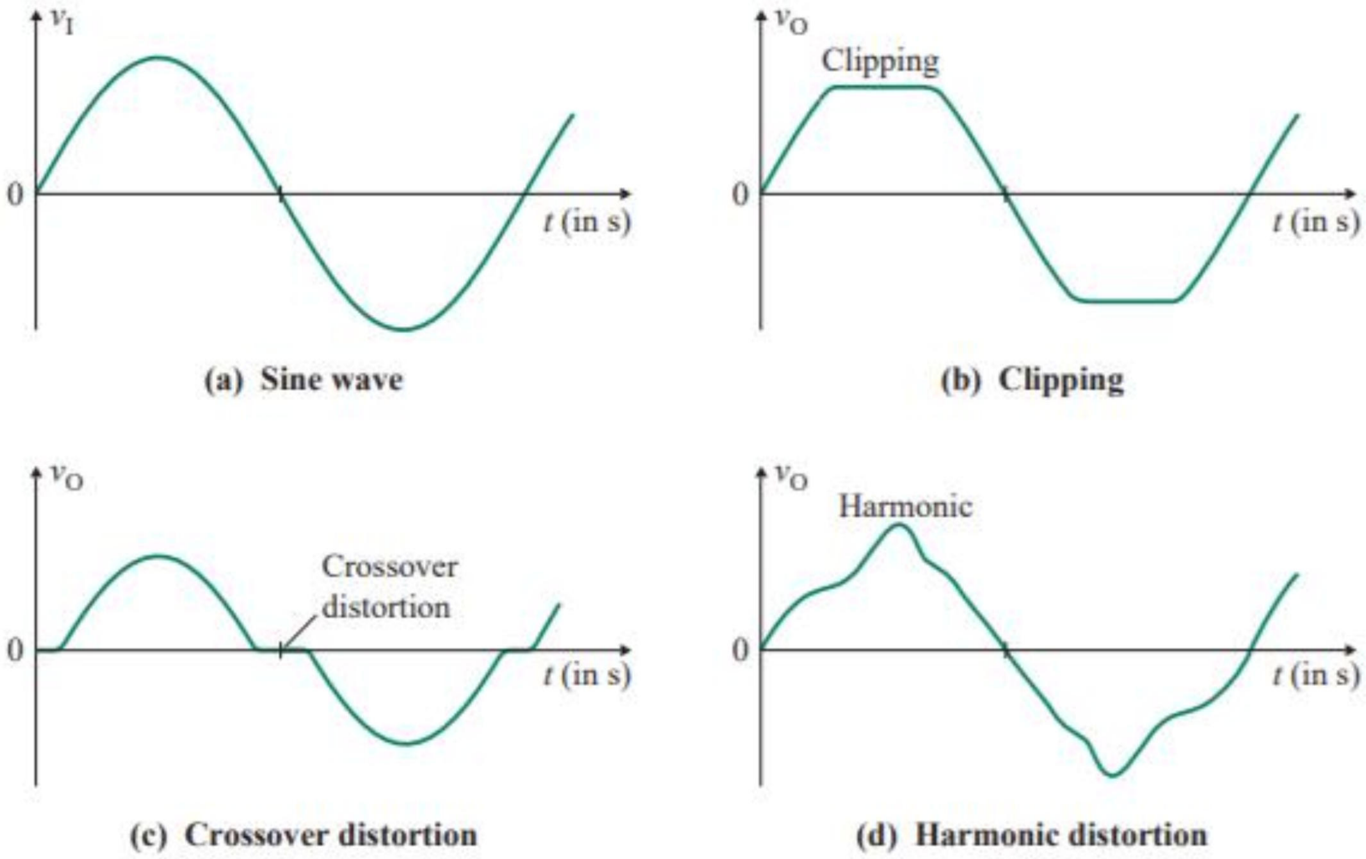
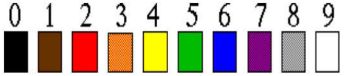


FIGURE 1.10 Some examples of distortion

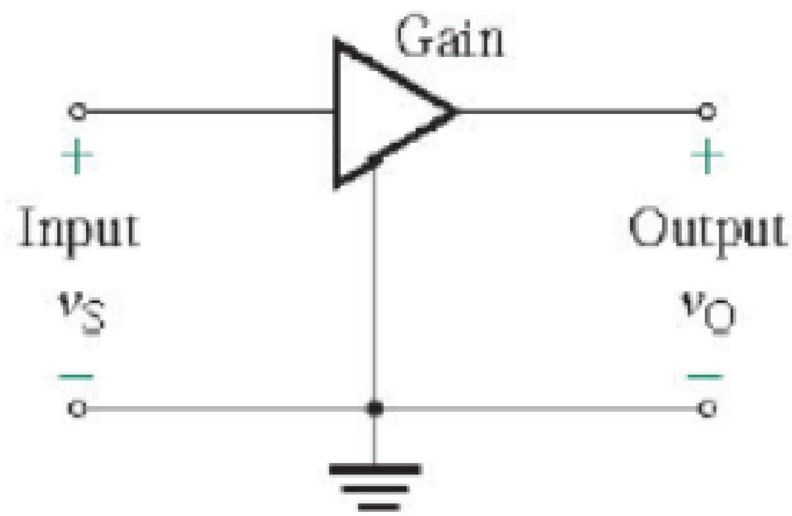
TABLE 1.3 Bandwidths of electronic signals

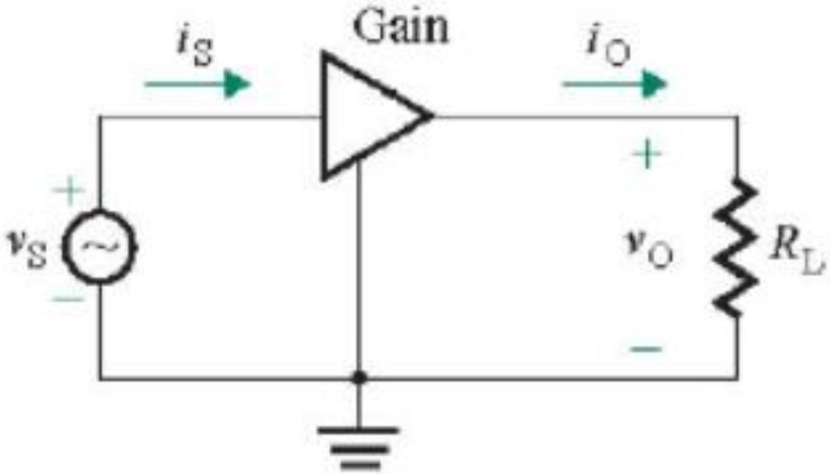
Signal Type	Bandwidth
Seismic signals	1 Hz to 200 Hz
Electrocardiograms	0.05 Hz to 100 Hz
Audio signals	20 Hz to 15 kHz
Video signals	DC to 4.2 MHz
AM radio signals	540 kHz to 1600 kHz
Radar signals	1 MHz to 100 MHz
VHF TV signals	54 MHz to 60 MHz
FM radio signals	88 MHz to 806 MHz
UHF TV signals	470 MHz to 806 MHz
Cellular telephone signals	824 MHz to 891.5 MHz
Satellite TV signals	3.7 GHz to 4.2 GHz
Microwave communication signals	1 GHz to 50 GHz



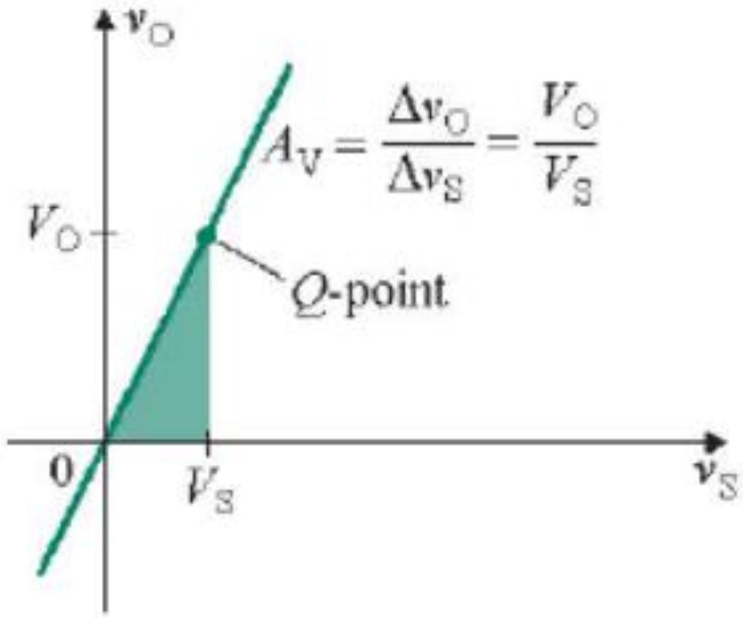
2.2 Amplifier Characteristics

An amplifier may be considered as a two-port network with an input port and an output port. It is represented by the circuit symbol shown in Fig. 2.1, which indicates the direction of signal flow from the input side to the output side. Normally, one of the input terminals is connected to one of the output terminals to form a *common ground*. The output voltage (or current) is related to the input voltage (or current) by a *gain parameter*. If the output signal is directly proportional to the input signal such that the output is an exact replica of the input signal, the amplifier is said to be a *linear amplifier*. If there is any change in the output waveform, it is considered to have *distortion*, which is undesirable. The amplifier is then said to

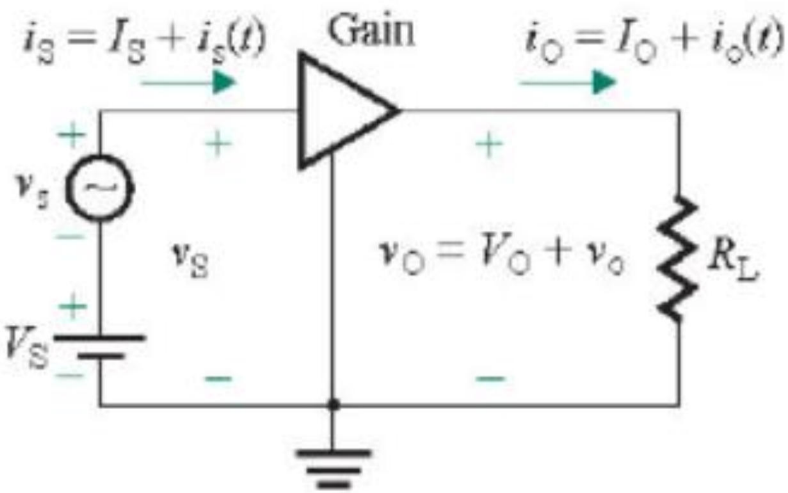




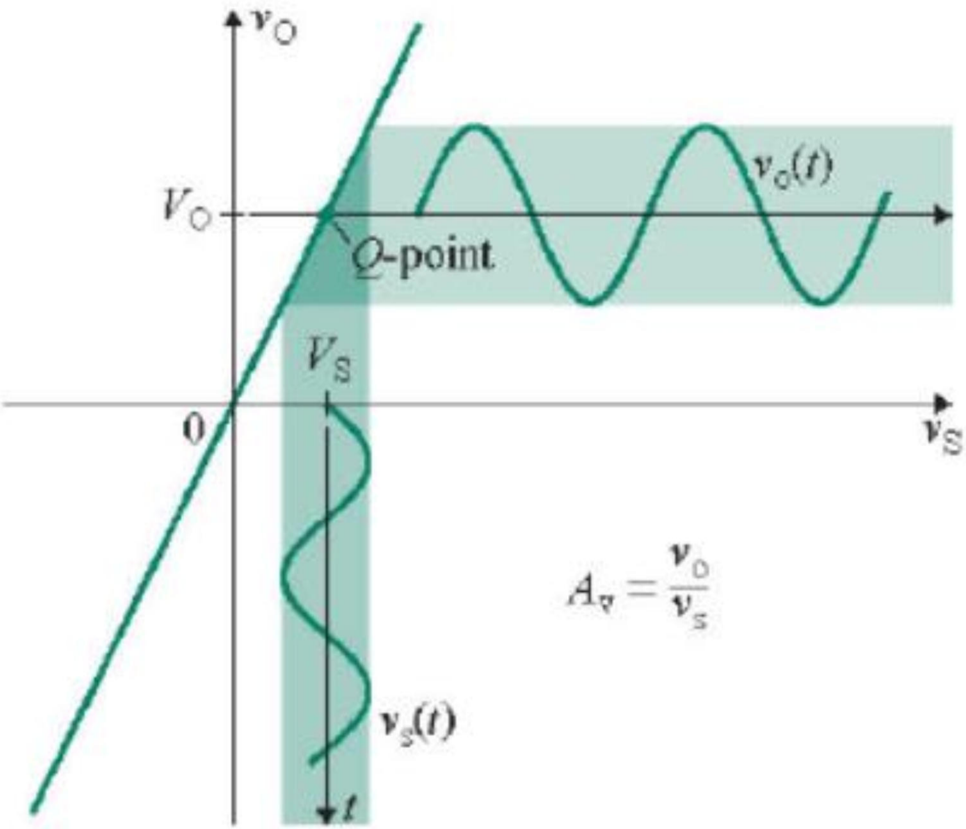
(a) Voltage amplifier



(b) Transfer characteristic



(c) Small signal imposed on DC signal



(d) Small-signal output voltage

2.2.1 Voltage Gain

If the input signal voltage to a linear amplifier is v_S, the amplifier will provide an output voltage v_O, which will be a magnified facsimile of v_S. This situation is shown in Fig. 2.2(a) for an amplifier with a load resistance of R_L. The *voltage gain* A_V of the amplifier is defined by

$$\boxed{\text{Voltage gain } A_V = \frac{\text{Output voltage } v_O}{\text{Input voltage } v_S} (\mathrm{V/V})} \qquad (2.1)$$

The transfer characteristic, shown in Fig. 2.2(b), will be a straight line with a slope of A_V. Thus, if we apply a DC input signal of $v_S = V_S$, the DC output voltage will be $v_O = V_O = A_V V_S$ and the amplifier will operate at point Q. The DC voltage gain then becomes $A_V = V_O / V_S$. However, if we superimpose a small sinusoidal signal $v_s = V_m \sin \omega t$ on V_S, as shown in Fig. 2.2(c), the output voltage becomes $v_O = V_O + v_o$.

The small-signal AC voltage gain becomes $A_v = \Delta v_O / \Delta v_S = v_o / v_s$. Thus, a small-signal input voltage $v_s = V_m \sin \omega t$ will give a corresponding small-signal output voltage $v_o = A_v V_m \sin \omega t$ such that $v_O = A_V V_S + A_v v_s = V_O + A_v V_m \sin \omega t$. This is shown in Fig. 2.2(d). Therefore, we face two voltage gains: a DC gain and a small-signal gain. For a linear amplifier, the two gains are equal. That is, $A_V = A_v$, and the small-signal gain is referred to simply as the *voltage gain*.

2.2.2 Current Gain

If i_S is the current the amplifier draws from the signal source and i_O is the current the amplifier delivers to the load R_L, then the *current gain* A_I of the amplifier is defined by

$$\boxed{\text{Current gain } A_I = \frac{\text{Load current } i_O}{\text{Input current } i_S} \text{(A/A)}} \qquad (2.2)$$

The transfer characteristic will be similar to that shown in Fig. 2.2(b). For a linear amplifier, the DC gain equals the small-signal current gain: $A_i = \Delta i_O / \Delta i_S = i_o / i_s$. That is, $A_I = A_i$, and the small-signal gain is referred to simply as the *current gain*.

2.2.3 Power Gain

An amplifier provides the load with greater power than it receives from the signal source. Thus, an amplifier has a *power gain* A_p, which is defined by

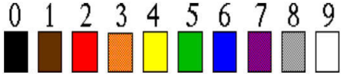
$$\boxed{\text{Power gain } A_p = \frac{\text{Load power } P_L}{\text{Input power } P_i}} \tag{2.3}$$

$$= \frac{v_o i_o}{v_s i_s} (\text{W/W}) \tag{2.4}$$

After substitution of $A_v = v_o / v_s$ and $A_i = i_o / i_s$, Eq. (2.4) can be written as

$$\boxed{A_p = A_v A_i} \tag{2.5}$$

Thus, the power gain is the product of the voltage gain and the current gain.



2.2.4 Logarithmic Gain

The gains of amplifiers can be expressed either as dimensionless quantities or with units (V/V for a voltage gain, A/A for a current gain, or W/W for a power gain). Their values are usually very large and extend over several orders of magnitude. It is not convenient to plot such large numbers against other parameters. Gains are normally expressed in terms of logarithms, as follows:

$$\text{Power gain in decibels (dB)} = 10 \log A_p = 10 \log_{10}\left(\frac{P_L}{P_i}\right) = 10 \log_{10}\left(\frac{v_o^2/R_L}{v_s^2/R_i}\right)$$

$$= 20 \log_{10}\left(\frac{v_o}{v_s}\right) + 10 \log_{10}\left(\frac{R_i}{R_L}\right)$$

$$\boxed{\text{Voltage gain in dB} = 20 \log |A_v|} \quad \text{for } R_i = R_L$$

The power gain can also be expressed in terms of the input and output current:

$$\boxed{\text{Power gain in dB} = 10 \log A_p} = 10 \log_{10}\left(\frac{P_L}{P_i}\right) = 10 \log_{10}\left(\frac{i_o^2 R_L}{i_s^2 R_i}\right)$$

$$= 20 \log_{10}\left(\frac{i_o}{i_s}\right) + 10 \log_{10}\left(\frac{R_L}{R_i}\right)$$

The term $20 \log_{10} (i_o/i_s)$ is referred to as the current gain of the amplifier in decibels. That is,

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

If $R_i = R_L$, the power gain in decibels is equal to the voltage and current gains in decibels. That is,

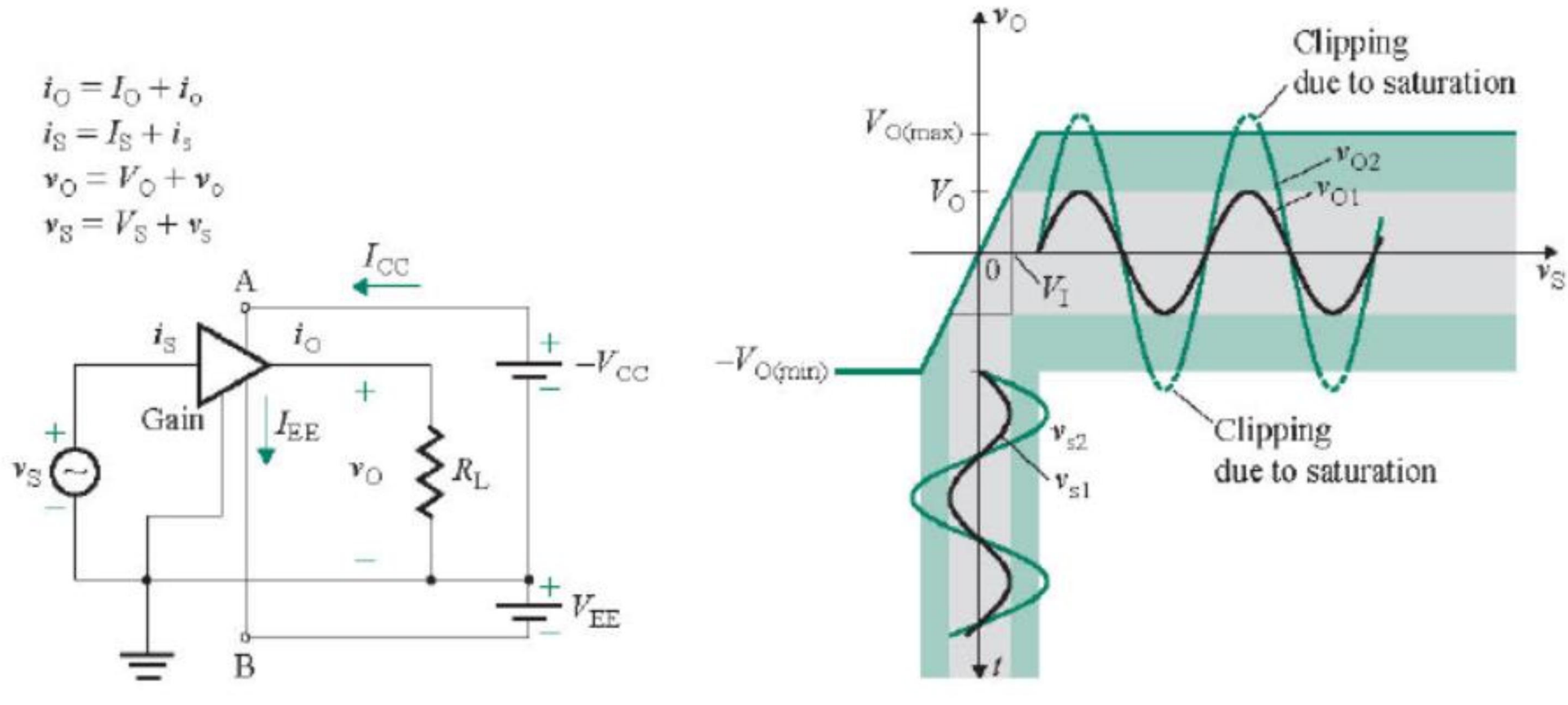
Input resistance

Input resistance R_i is a measure of the current drawn by the amplifier. It is a ratio of the input signal volt
to the input current:

$$R_{\mathrm{i}} = \frac{v_{\mathrm{S}}}{i_{\mathrm{S}}}$$

2.2.6 Amplifier Saturation

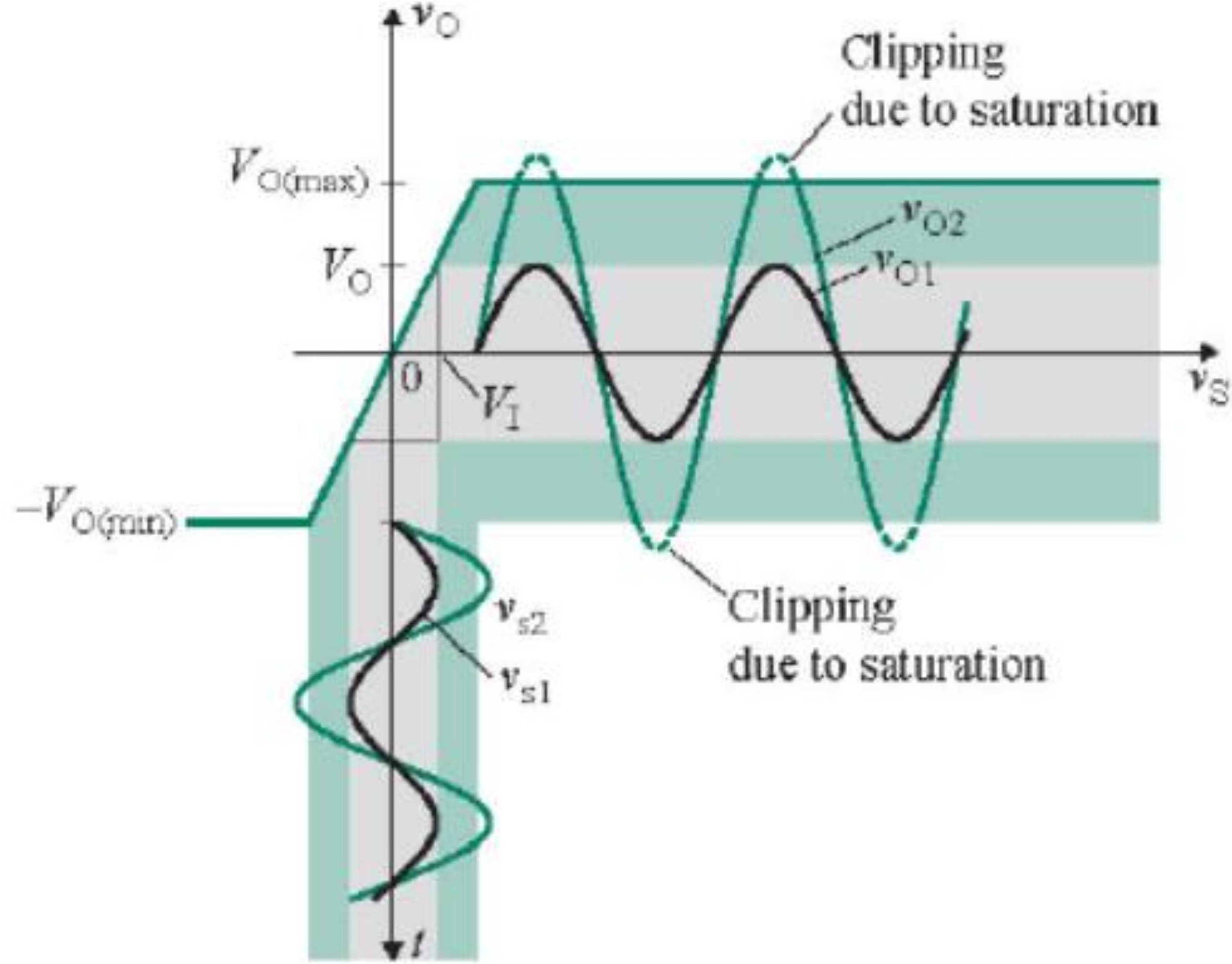
An amplifier needs a DC power supply (or supplies) so that an operating Q-point can be established, as shown in Fig. 2.2(b), that allows variation in the output signal in response to a small change in the input signal. The DC supply (or supplies) provides the power delivered to the load, as well as any power that is dissipated as heat within the amplifier itself. An amplifier with two power supplies, V_{CC} and V_{EE}, is shown in



(a) Amplifier with DC supplies

(b) Effect of saturation

FIGURE 2.3 Amplifier power supplies and saturation



(b) Effect of saturation

Each of the two saturation limits is usually within 1 V or 2 V of the corresponding power supply. This fact is a consequence of the internal circuity of the amplifiers and the nonlinear behavior of the amplifying devices. Therefore, to avoid distortion of the output voltage as shown in Fig. 2.3(b), the input voltage must be kept within the range defined by

$$\boxed{\frac{-V_{O(\min)}}{A_V} \leq v_S \leq \frac{V_{O(\max)}}{A_V}} \tag{2.7}$$

As long as the amplifier operates with the saturation limits, the voltage gain can normally be assumed to be linear. The power delivered by the DC supplies will be

$$\boxed{P_{dc} = V_{CC}I_{CC} + V_{EE}I_{EE}} \tag{2.8}$$

and the power delivered P_i by the input signal will be small compared to P_{dc}. Therefore, the efficiency η of an amplifier is defined by

$$\boxed{\text{Amplifier efficiency } \eta = \frac{\text{Load power } P_L}{\text{Power delivered by DC supplies } P_{dc}}} \tag{2.9}$$

The efficiency of an amplifier ranges from 25% to 80%, depending on the type of amplifier. For amplifiers with a very low input signal (millivolts or microvolts), the voltage gain rather than the efficiency is the prime consideration. On the other hand, for power amplifiers (covered in Chapter 11), efficiency is the major

Ex:1

Finding amplifier parameters The measured small-signal values of the linear amplifier in Fig. 2.3(a) are $v_s = 20 \sin 400t$ (mV), $i_s = 1 \sin 400t$ (μA), $v_o = 7.5 \sin 400t$ (V), and $R_L = 0.5$ kΩ. The DC values are $V_{CC} = V_{EE} = 12$ V and $I_{CC} = I_{EE} = 10$ mA. Find **(a)** the values of amplifier parameters A_v, A_i, A_p, and R_i; **(b)** the power delivered by DC supplies P_{dc} and the power efficiency η; and **(c)** the maximum value of the input voltage so that the amplifier operates within the saturation limits.

SOLUTION

SOLUTION

$v_{s(peak)} = 20$ mV, $v_{o(peak)} = 7.5$ V, and $i_{s(peak)} = 1\ \mu$A.

(a) The load current is

$$i_o = \frac{v_o}{R_L} = \frac{7.5 \sin 400t \text{ (V)}}{0.5 \text{ k}\Omega} = 15 \times 10^{-3} \sin 400t = 15 \sin 400t \text{ (mA)}$$

The voltage gain is

$$A_v = \frac{v_{o(peak)}}{v_{s(peak)}} = \frac{7.5 \text{ V}}{20 \text{ mV}} = 375 \text{ V/V} \qquad [\text{or } 20 \log (375) = 51.48 \text{ dB}]$$

The current gain is

$$A_i = \frac{i_{o(peak)}}{i_{s(peak)}} = \frac{15 \text{ mA}}{1\ \mu\text{A}} = 15 \text{ kA/A} \qquad [\text{or } 20 \log (15 \text{ k}) = 83.52 \text{ dB}]$$

The power gain is

$$A_p = A_v A_i = 375 \times 15\ \text{k} = 5625\ \text{kW/W} \qquad [\text{or } 10 \log (5625\ \text{k}) = 67.5\ \text{dB}]$$

The input resistance is

$$R_i = \frac{v_{s(\text{peak})}}{i_{s(\text{peak})}} = \frac{20\ \text{mV}}{1\ \mu\text{A}} = 20\ \text{k}\Omega$$

(b) The power delivered by the DC supplies is

$$P_{dc} = V_{CC} I_{CC} + V_{EE} I_{EE} = 2 \times 12\ \text{V} \times 10\ \text{mA} = 240\ \text{mW}$$

The load power is

$$P_L = \left(\frac{v_{o(\text{peak})}}{\sqrt{2}}\right)\left(\frac{i_{o(\text{peak})}}{\sqrt{2}}\right) = \left(\frac{7.5\text{ V}}{\sqrt{2}}\right)\left(\frac{15\text{ mA}}{\sqrt{2}}\right) = 56.25\text{ mW}$$

By using $\sqrt{2}$ factor for converting a peak value to a rms value, the input power is

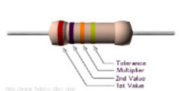
$$P_i = \left(\frac{v_{s(\text{peak})}}{\sqrt{2}}\right)\left(\frac{i_{s(\text{peak})}}{\sqrt{2}}\right) = \left(\frac{20\text{ mV}}{\sqrt{2}}\right)\left(\frac{1\ \mu\text{A}}{\sqrt{2}}\right) = 10\text{ mW}$$

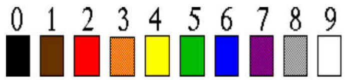
The power efficiency is

$$\eta = \frac{P_L}{P_{dc}+P_i} = \frac{56.25\text{ mW}}{250\text{ mW}} = 22.5\%$$

$$A_v v_{s(max)} = v_{O(max)} = V_{CC} = V_{EE} \qquad \text{or} \qquad v_{S(max)} = \frac{12\ \text{V}}{375} = 32\ \text{mV}$$

the limit of the maximum input voltage is $\boxed{0 \le v_{S(max)} \le 32\ \text{mV},}$ and the limit of the minimum input voltage is $\boxed{v_{S(min)} = -v_{S(max)} = -32\ \text{mV}.}$





2.2.7 Amplifier Nonlinearity

Practical amplifiers exhibit a nonlinear characteristic, which is caused by nonlinear devices such as transistors (discussed in Chapters 7 and 8). For the amplifier shown in Fig. 2.4(a) with one DC supply, its nonlinear characteristic is shown in Fig. 2.4(b). Fortunately there is a region in the midrange of the output

$$v_S(t) = V_S + v_s(t) = V_S + V_m \sin \omega t$$

which will cause the operating point to move up and down along the transfer characteristic around the Q-point. This movement will cause a corresponding time-varying output voltage

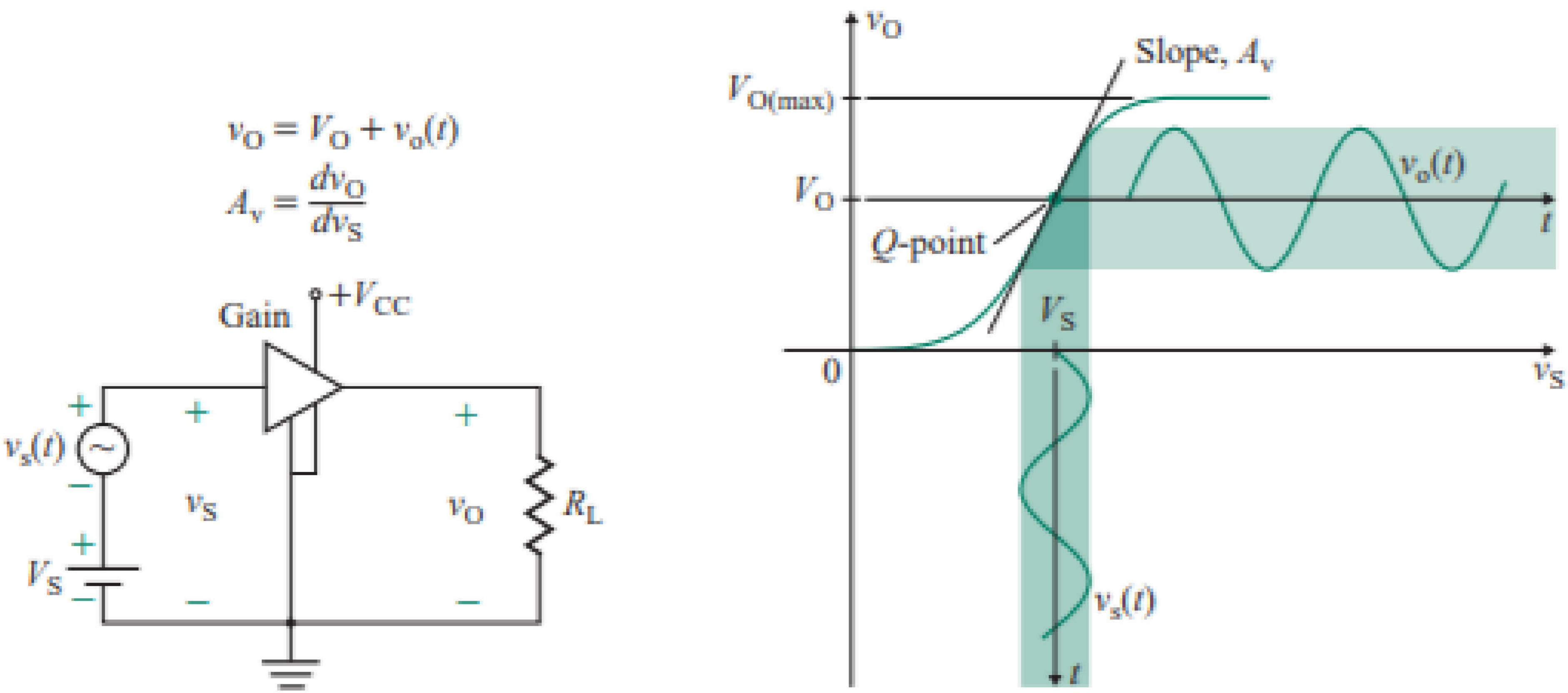
$$v_O(t) = V_O + v_o(t)$$

If $v_s(t)$ is sufficiently small, then $v_o(t)$ will be directly proportional to $v_s(t)$; so

$$v_o(t) = A_v v_s(t) = A_v V_m \sin \omega t$$

where A_v is the slope of the transfer characteristic at the Q-point. That is,

$$A_v = \left. \frac{dv_O}{dv_S} \right|_{\text{at } Q\text{-point}} \tag{2.10}$$



(a) Nonlinear amplifier **(b) Nonlinear characteristics**

Ex:2

Finding the limiting parameters of a nonlinear amplifier The measured values of the nonlinear amplifier in Fig. 2.4(a) are $v_O = 4.3$ V at $v_S = 18$ mV, $v_O = 5$ V at $v_S = 20$ mV, and $v_O = 5.8$ V at $v_S = 22$ mV. The DC supply voltage is $V_{CC} = 9$ V, and the saturation limits are $2\text{ V} \le v_O \le 8\text{ V}$.

(a) Determine the small-signal voltage gain A_v.

(b) Determine the DC voltage gain A_{dc}.

(c) Determine the limits of input voltage v_S.

Let $v_O = 5$ V at $v_S = 20$ mV be the Q-point. Then

$$\Delta v_O = v_O(\text{at } v_S = 22 \text{ mV}) - v_O(\text{at } v_S = 18 \text{ mV}) = 5.8 \text{ V} - 4.3 \text{ V} = 1.5 \text{ V}$$

$$\Delta v_S = v_S(\text{at } v_O = 5.8 \text{ V}) - v_S(\text{at } v_O = 4.3\text{V}) = 22 \text{ mV} - 18 \text{ mV} = 4 \text{ mV}$$

(a) The small-signal voltage gain is

$$A_v = \frac{\Delta v_O}{\Delta v_S} = \frac{1.5 \text{ V}}{4 \text{ mV}} = 375 \text{ V/V} \qquad (\text{or } 51.48 \text{ dB})$$

(b) The DC voltage gain is

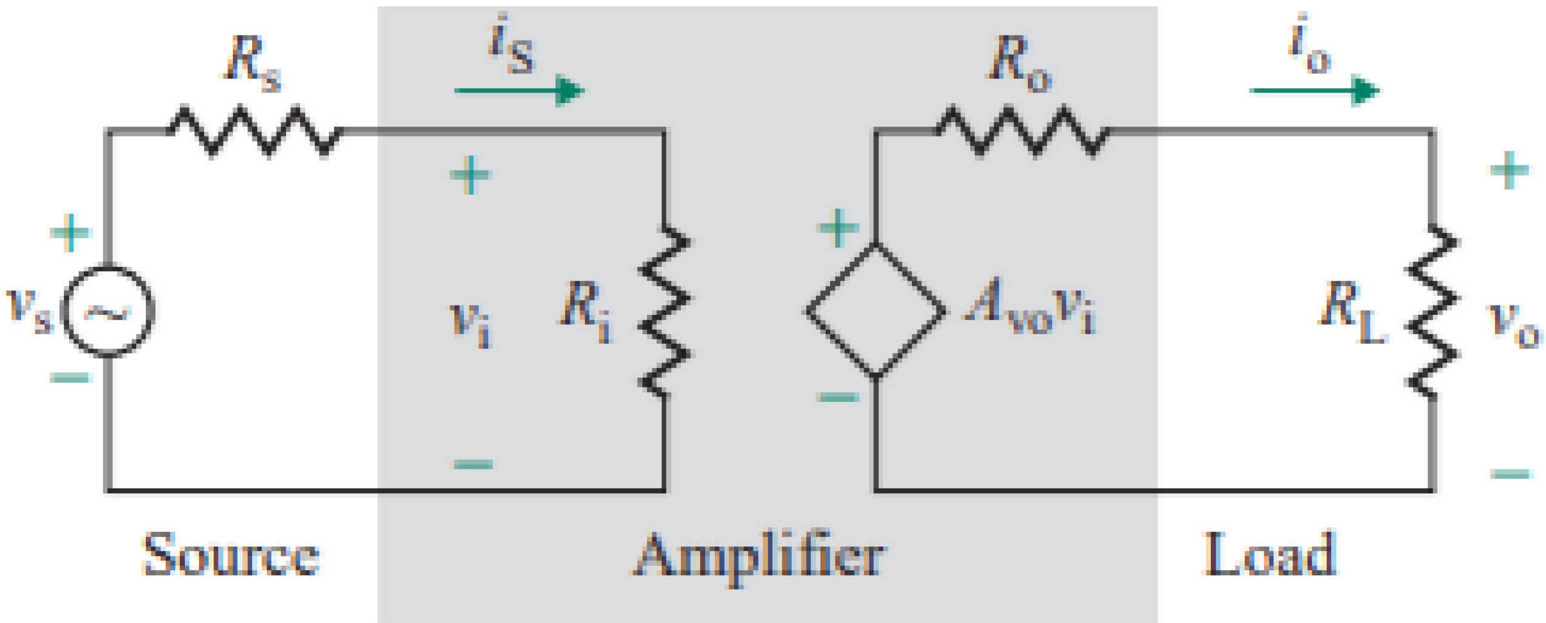
$$A_{dc} = A_V = \frac{v_O}{v_S} = \frac{5\ \text{V}}{20\ \text{mV}} = 250\ \text{V/V} \qquad (\text{or } 47.96\ \text{dB})$$

(c) The limits of input voltage v_S are

$$\frac{-(v_O - v_{O(\min)})}{A_v} \le v_S - 20\ \text{mV} \le \frac{(v_{O(\max)} - v_O)}{A_v}$$

That is, $-(5-2)/A_V \le v_S - 20\ \text{mV} \le (8-5)/A_V$, or $-8\ \text{mV} \le v_S - 20\ \text{mV} \le 8\ \text{mV}$,

Types of Amplifiers:



(a) Small-signal equivalent circuit of a voltage amplifier

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

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

Types of Amplifiers:

$$\boxed{A_v = \frac{v_o}{v_s} = \frac{v_o}{v_i} \times \frac{v_i}{v_s} = \frac{A_{vo} R_i R_L}{(R_i + R_s)(R_L + R_o)}} = \frac{A_{vo}}{(1 + R_s/R_i)(1 + R_o/R_L)}$$

rrent gain A_i, which is defined as the ratio of the output current i_o to the input

$$\boxed{A_i = \frac{i_o}{i_s} = \frac{A_{vo} v_i}{R_L + R_o} \times \frac{1}{v_i/R_i} = \frac{A_{vo} R_i}{R_L + R_o}}$$

Ex:3

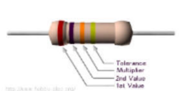
Determining the design specifications of a voltage amplifier A voltage amplifier is required to amplify the output signal from a communication receiver that produces a voltage signal of $v_s = 20$ mV with an internal resistance of $R_s = 1.5$ kΩ. The load resistance is $R_L = 15$ kΩ. The desired output voltage is $v_o \geq 10$ V. The amplifier must not draw more than 1 μA from the receiver. The variation in output voltage when the load is disconnected should be less than 0.5%. Determine the design specifications of the voltage amplifier.

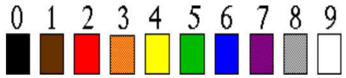
$$V_s = 20\ mV$$

$$R_s = 1.5\ k\Omega\ \&\ R_L = 15\ k\Omega$$

$$V_o \geq 10V\ \ \&\ I_s \leq 1\ \mu A$$

$$\frac{\Delta V_o}{V_o} \leq 0.5\%\ \ \&\ R_o \leq 75\Omega$$





SOLUTION

Since the input current is $i_s \le 1\ \mu\text{A}$, the input resistance of the amplifier can be found from

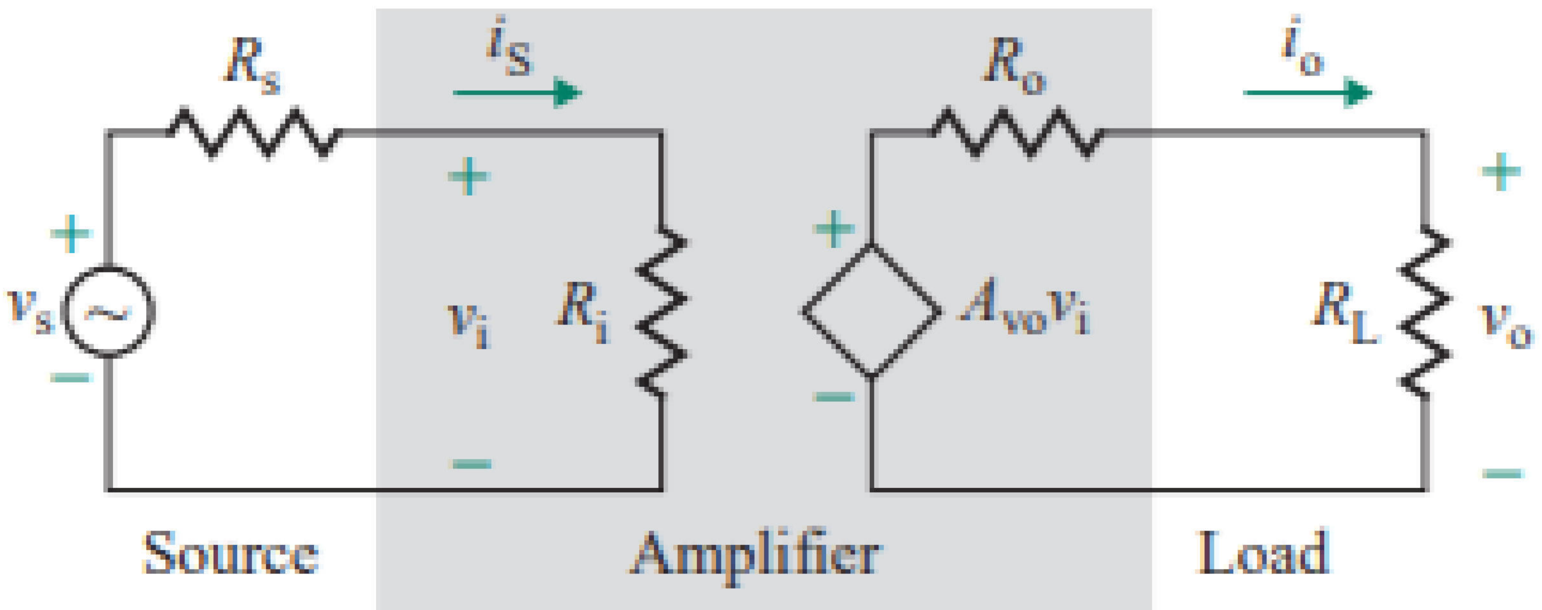
$$R_s + R_i = \frac{v_s}{i_s} \ge \frac{20\ \text{mV}}{1\ \mu\text{A}} = 20\ \text{k}\Omega$$

which gives

$$R_i \ge 20\ \text{k}\Omega - R_s = 20\ \text{k}\Omega - 1.5\ \text{k}\Omega = 18.5\ \text{k}\Omega$$

Types of Amplifiers:

$$A_v = \frac{v_o}{v_s} = \frac{v_o}{v_i} \times \frac{v_i}{v_s} = \frac{A_{vo} R_i R_L}{(R_i + R_s)(R_L + R_o)} = \frac{A_{vo}}{(1 + R_s/R_i)(1 + R_o/R_L)}$$



(a) Small-signal equivalent circuit of a voltage amplifier

$$A_V = \frac{V_o}{V_s} = \frac{10V}{20}mV = 500\ \ V/V$$

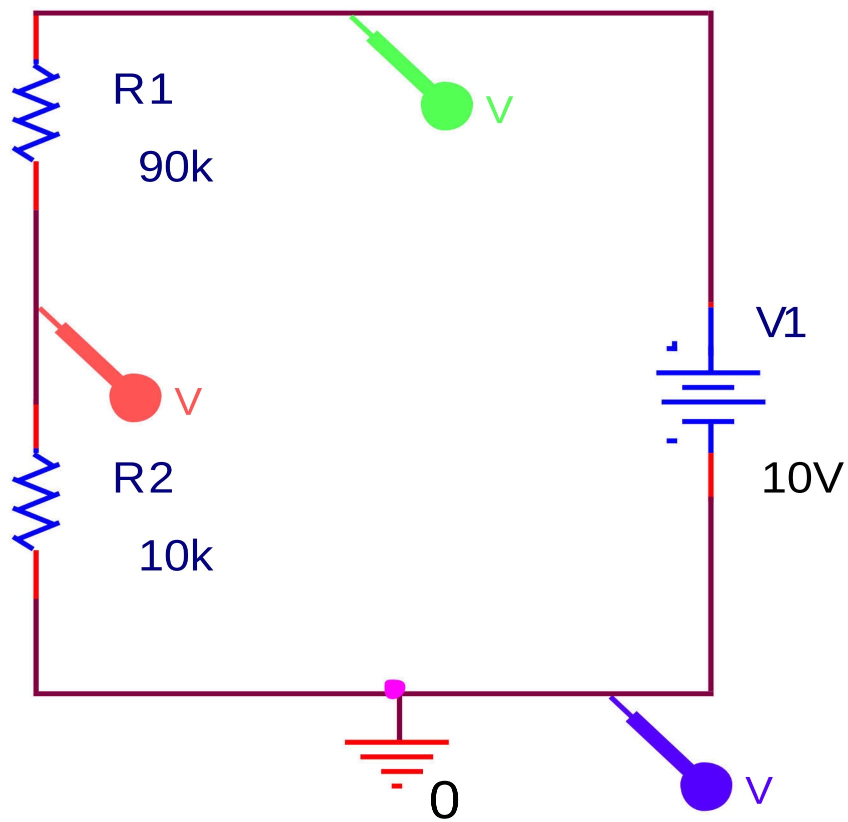
$$\frac{\Delta v_o}{v_o} = \frac{R_o}{R_L + R_o}$$

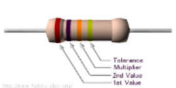
$$500 \leq \frac{A_{vo}}{(1 + R_s/R_i)(1 + R_o/R_L)} = \frac{A_{vo}}{(1 + 1.5\text{ k}/18.5\text{ k})(1 + 75/15\text{ k})}$$

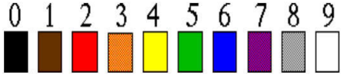
2 Minute Quiz

Name_______________ Section _____

- What is the voltage measured by the blue probe?
- What is the voltage measured by the green probe?
- What is the voltage measured by the red probe?



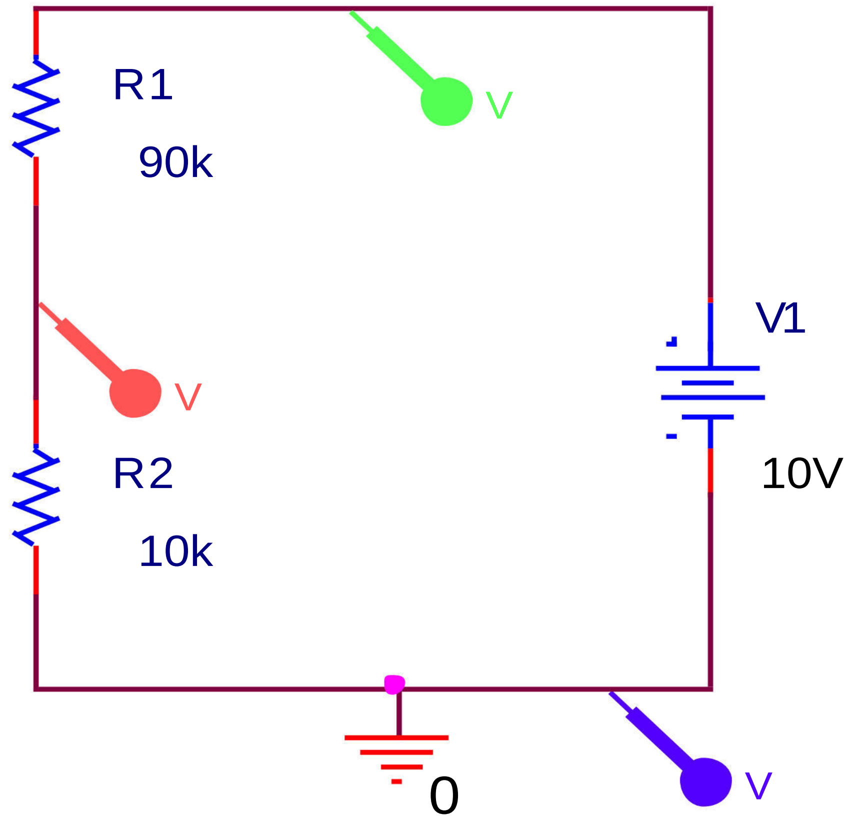


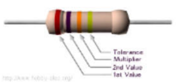


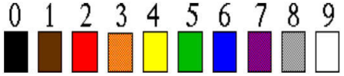
Answers

- The green probe: 10V
- The red probe: 1V
- The blue probe: 0V
- Voltage Divider:

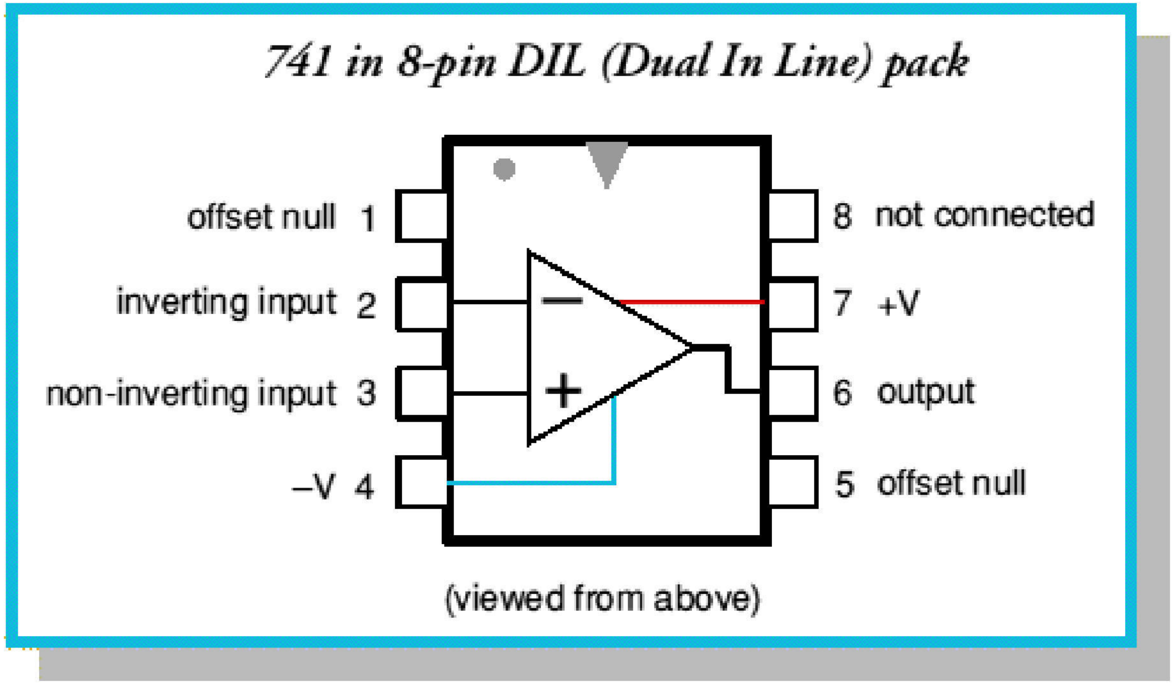
$$V = \frac{R_2}{R_1 + R_2} 10V$$







Op-Amps: Practical Issues



Note: Literally a Black Box

- We use real op-amps: 741
- Note the pin connections for the IC