BENHA UNIVERSITY
FACULTY OF ENGINEERING AT SHOUBRA

ECE-322
Electronic Circuits (B)

Lecture #2
Operational Amplifiers

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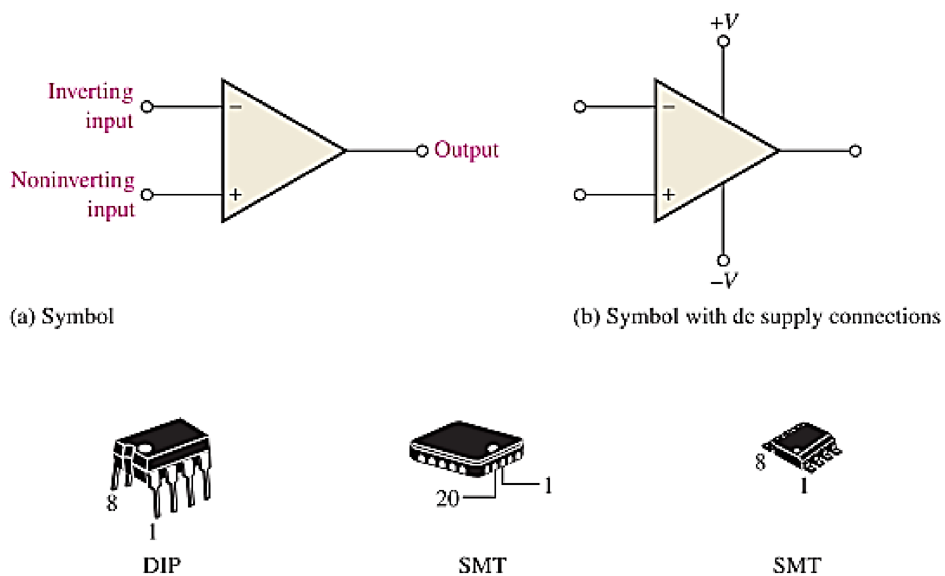
Agenda

- Introduction
- Op-Amps Input Modes and Parameters
- Op-Amps with Negative Feedback
- Bias Current and Offset Voltage
- Open & Closed Loop Frequency Responses

INTRODUCTION

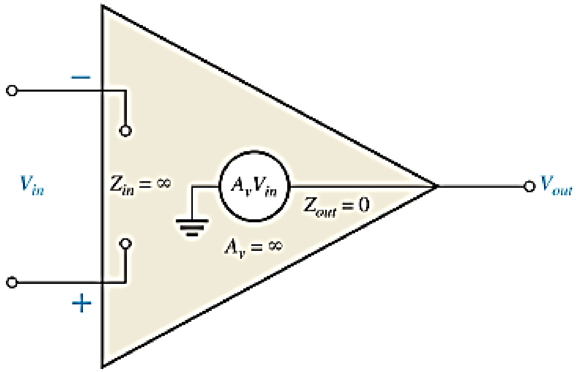
Introduction to Op-Amps

- Early operational amplifiers (op-amps) were used primarily to perform mathematical operations such as addition, subtraction, integration, and differentiation—thus the term **operational**.
- These early devices were constructed with vacuum tubes and worked with high voltages.
- Today's op-amps are linear integrated circuits (**ICs**) that use relatively low dc supply voltages and are reliable and inexpensive.

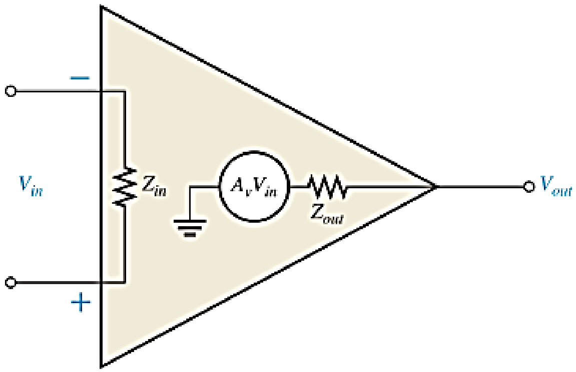


(c) Typical packages. Pin 1 is indicated by a notch or dot on dual in-line (DIP) and surface-mount technology (SMT) packages, as shown.

Ideal & Practical Op-Amp

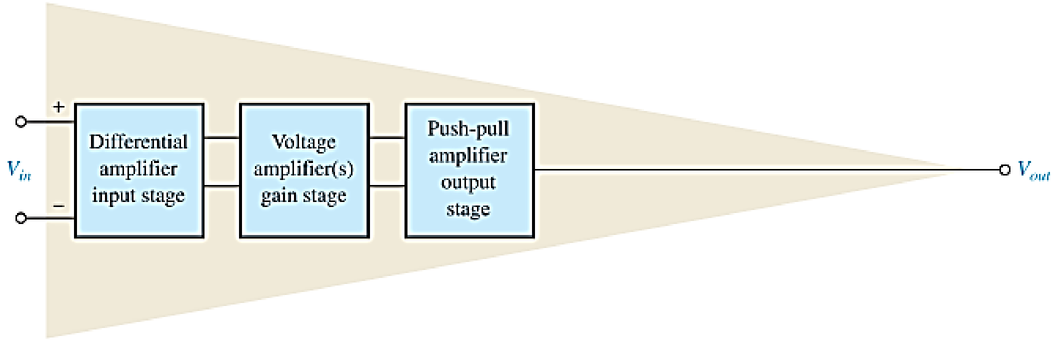


(a) Ideal op-amp representation

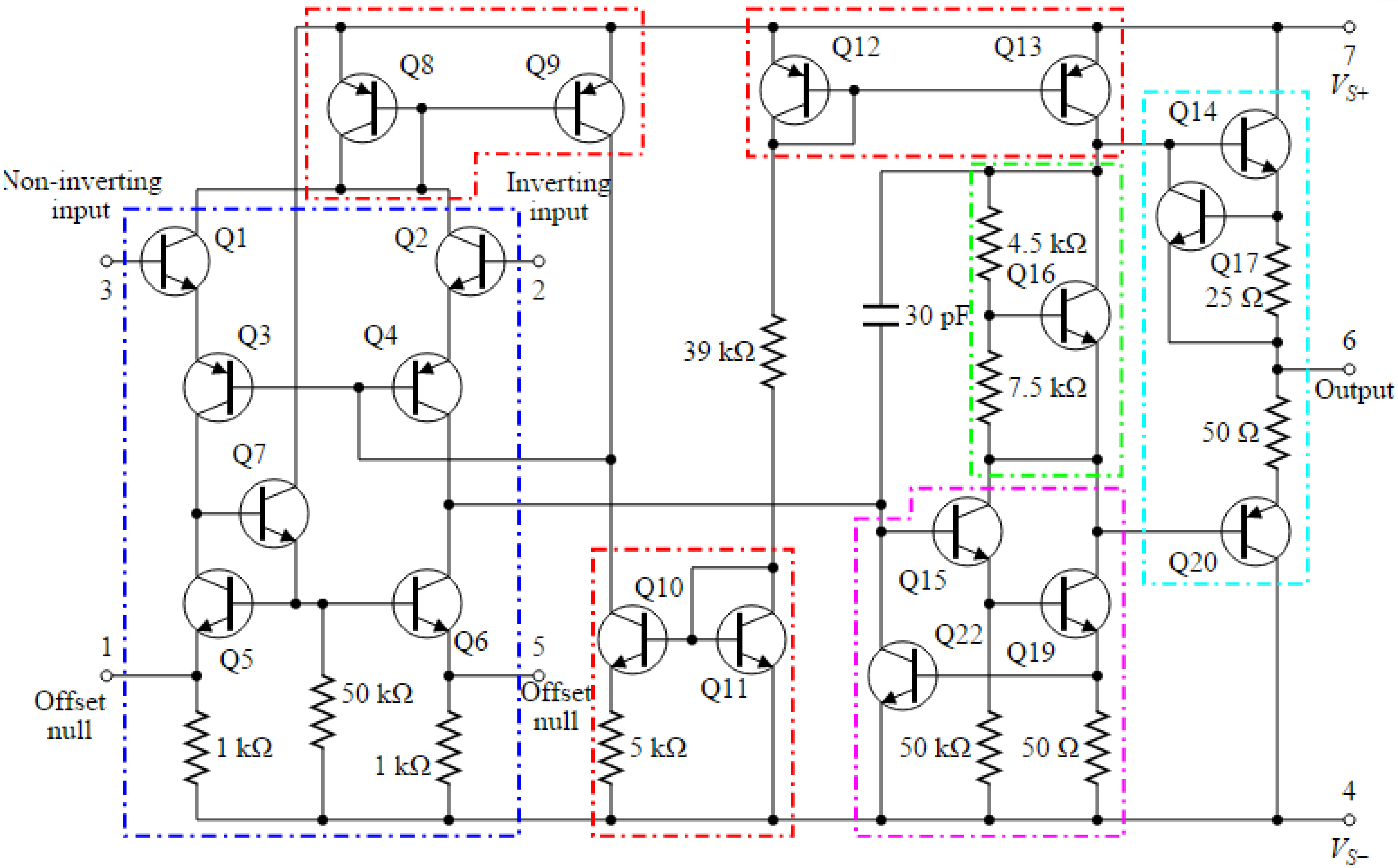


(b) Practical op-amp representation

- **Internal Block Diagram of an Op-Amp**



741 Op-Amp Internal Circuit

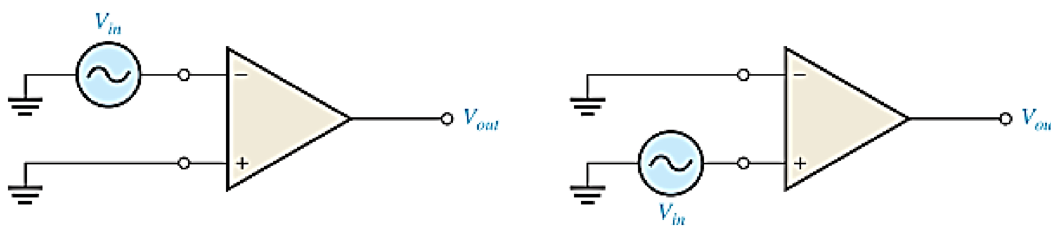


A component-level diagram of the common 741 op-amp. Dotted lines outline: current mirrors (red); differential amplifier (blue); class A gain stage (magenta); voltage level shifter (green); output stage (cyan).

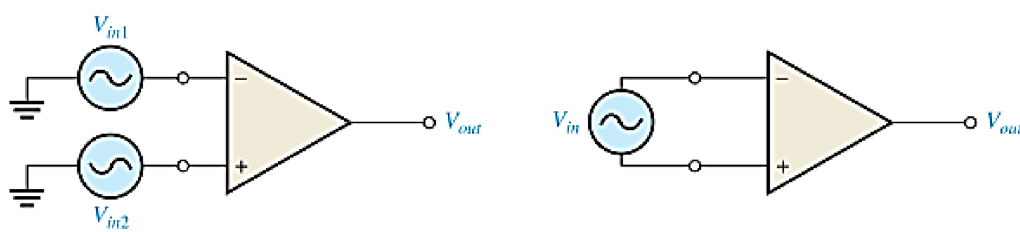
OP-AMPS INPUT MODES AND PARAMETERS

Input Signal Modes

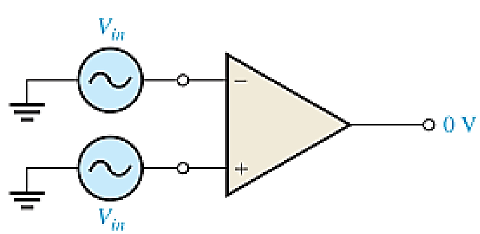
- **Single-ended differential mode**



- **Double-ended differential mode**



- **Common-mode operation**



Op-Amp Parameters
Common-Mode Rejection Ratio

- The common-mode rejection ratio, **CMRR**:

It's the ratio of the open-loop differential voltage gain, $\mathbf{A_{ol}}$, to the common-mode gain, $\mathbf{A_{cm}}$.

$$\text{CMRR} = \frac{A_{ol}}{A_{cm}} \qquad \text{CMRR} = 20 \log\left(\frac{A_{ol}}{A_{cm}}\right)$$

- *Open-loop voltage gain* can range up to 200,000 (106 dB) and is not a well-controlled parameter.
- Datasheets often refer to the open-loop voltage gain as the *large-signal voltage gain*.
- A CMRR of 100,000, for example, means that the desired input signal (differential) is amplified 100,000 times more than the unwanted noise (common-mode).

Op-Amp Parameters..

Maximum Output Voltage Swing ($V_{O(p-p)}$)

- With no input signal, the output of an op-amp is ideally 0 V. This is called the quiescent output voltage.
- When an input signal is applied, the ideal limits of the peak-to-peak output signal are $\pm V_{cc}$.
- In practice this ideal can be approached but never reached.
- Vo_{pp} varies with the load connected to the op-amp and increases directly with load resistance.

Example:
Fairchild KA741

$V_{O(p-p)}$ of ± 13 V for $V_{CC} = \pm 15$ V when $R_L = 2\,k\Omega$

$V_{O(p-p)}$ increases to ± 14 V when $R_L = 10\,k\Omega$

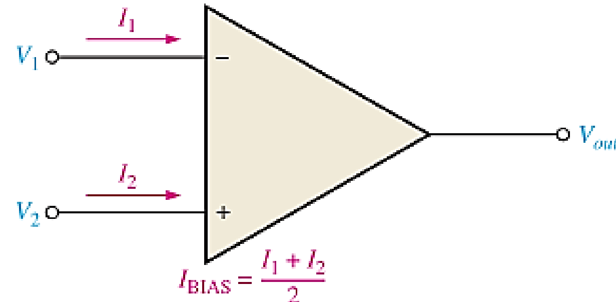
Input Offset Voltage:

- The ideal op-amp produces zero volts out for zero volts in.
- In a practical op-amp, a small dc voltage, $\mathbf{V_{OUT(error)}}$, appears at the output when no differential input voltage is applied.
- Its primary cause is a slight mismatch of the base-emitter voltages of the differential amplifier input stage of an op-amp.
- The input offset voltage, $\mathbf{V_{OS}}$, is the differential dc voltage required between the inputs to force the output to zero volts
- Typical values $\mathbf{V_{OS}}$, are in the range of 2 mV or less.

Op-Amp Parameters
Input Bias Current

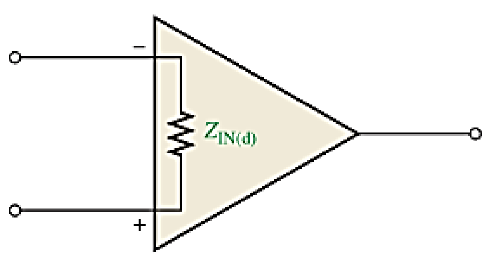
- The input bias current is the dc current required by the inputs of the amplifier to properly operate the first stage.
- Input bias current is the average of the two op-amp input currents

$$I_{BIAS} = \frac{I_1 + I_2}{2}$$

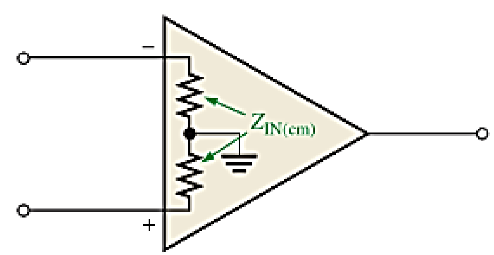


Input Impedance

- The differential input impedance is the total resistance between the inverting and the non-inverting inputs.
- The common-mode input impedance is the resistance between each input and ground and is measured by determining the change in bias current for a given change in common-mode input voltage.



(a) Differential input impedance



(b) Common-mode input impedance

Op-Amp Parameters…
Input Offset Current

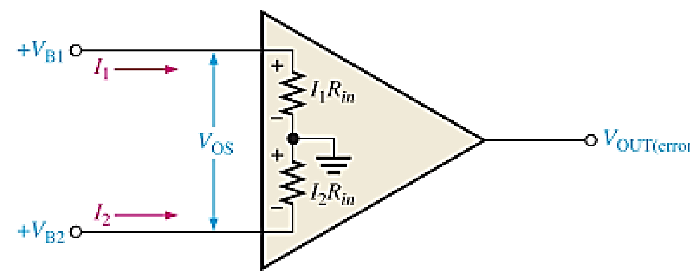
- Ideally, the two input bias currents are equal, and thus their difference is zero.
- In a practical op-amp, the bias currents are not exactly equal.
- The input offset current, IOS, is the difference of the input bias currents, expressed as an absolute value.

$$I_{OS} = |I_1 - I_2|$$

$$V_{OS} = I_1R_{in} - I_2R_{in} = (I_1 - I_2)R_{in}$$

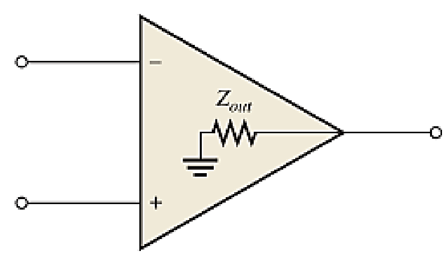
$$V_{OS} = I_{OS}R_{in}$$

$$V_{OUT(error)} = A_vI_{OS}R_{in}$$



Output Impedance

- The output impedance is the resistance viewed from the output terminal of the op-amp

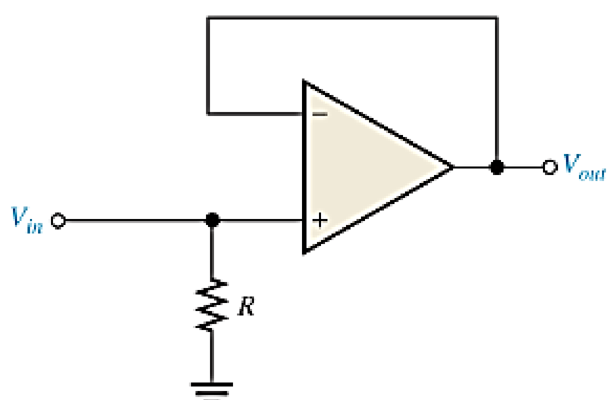


Op-Amp Parameters….
Slew Rate

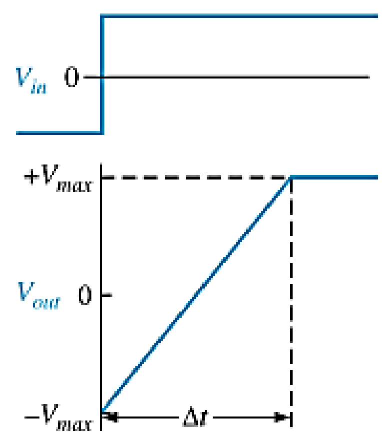
- The maximum rate of change of the output voltage in response to a step input voltage is the slew rate of an op-amp.
- The slew rate is dependent upon the high-frequency response of the amplifier stages within the op-amp.

$$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t}$$

- **Slew-rate measurement**



(a) Test circuit



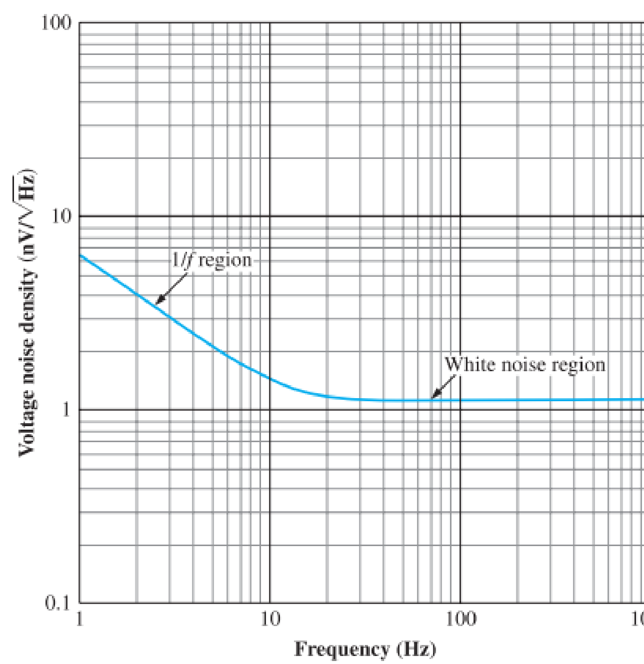
(b) Step input voltage and the resulting output voltage

Op-Amp Parameters…..
Frequency Response

- The internal amplifier stages that make up an op-amp have voltage gains limited by junction capacitances.
- An op-amp has no internal coupling capacitors, however; therefore, the low-frequency response extends down to dc (0 Hz).

Noise Specification

- Noise has become a more important issue !
- Noise is defined as an unwanted signal that affects the quality of a desired signal.
- There are two basic forms of noise.
- At low frequencies, noise is inversely proportional to the frequency; this is called 1/f noise or "**pink noise**".
- Above a critical noise frequency, the noise becomes flat and is spread out equally across the frequency spectrum; this is called "**white noise**".
- The power distribution of noise is measured in watts per hertz (W/Hz).

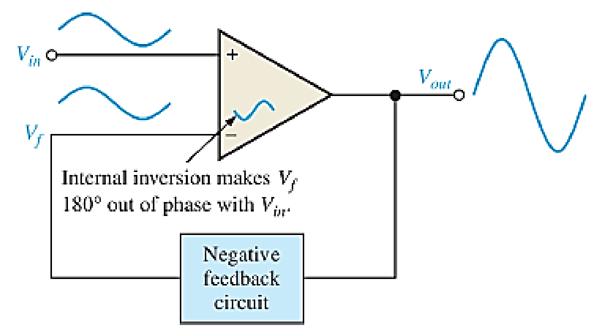


A Comparison of for some representative op-amps Parameters.
Check the reference !

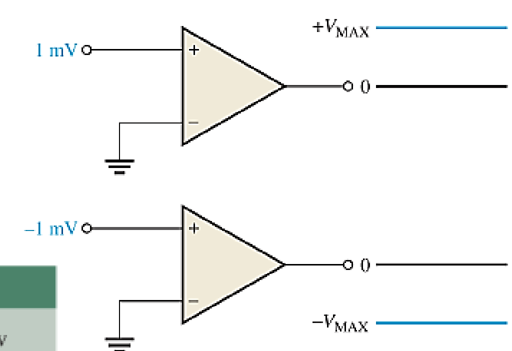
OP-AMPS WITH NEGATIVE FEEDBACK

Why Use Negative Feedback?

- **Negative feedback** is the process whereby a portion of the output voltage of an amplifier is returned to the input with a phase angle that opposes (or subtracts from) the input signal.



- Open-loop voltage gain of a typical op-amp is very high.
- Therefore, an extremely small input voltage drives the op-amp into its saturated output states.
- In fact, even the input offset voltage of the op-amp can drive it into saturation.



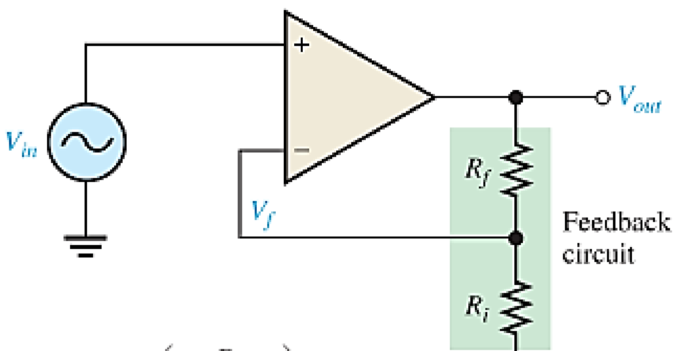
	VOLTAGE GAIN	INPUT Z	OUTPUT Z	BANDWIDTH
Without negative feedback	A_{ol} is too high for linear amplifier applications	Relatively high (see Table 12–1)	Relatively low	Relatively narrow (because the gain is so high)
With negative feedback	A_{cl} is set to desired value by the feedback circuit	Can be increased or reduced to a desired value depending on type of circuit	Can be reduced to a desired value	Significantly wider

OP-AMPS WITH NEGATIVE FEEDBACK

- An op-amp can be connected using negative feedback to stabilize the gain and increase frequency response.
- The closed-loop voltage gain is the voltage gain of an op-amp with external feedback.
- The closed-loop voltage gain is determined by the external component values and can be precisely controlled by them.

- **Non-inverting Amplifier**

$$A_{cl(NI)} = 1 + \frac{R_f}{R_i}$$



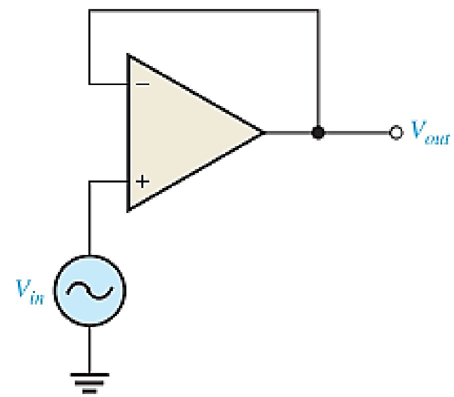
$$V_f = \left(\frac{R_i}{R_i + R_f}\right)V_{out}$$

Assignment: Derive the A_{cl} for Non-inverting and Inverting Amplifiers.

OP-AMPS WITH NEGATIVE FEEDBACK..

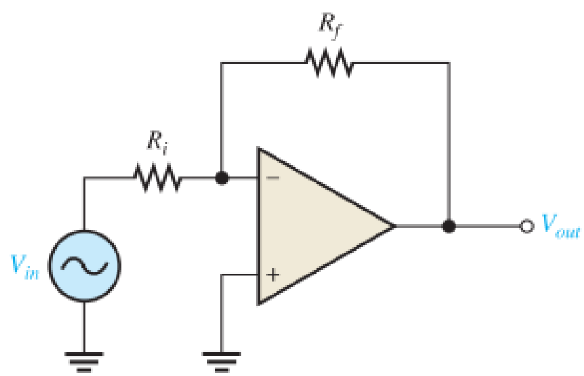
- **Voltage-Follower**

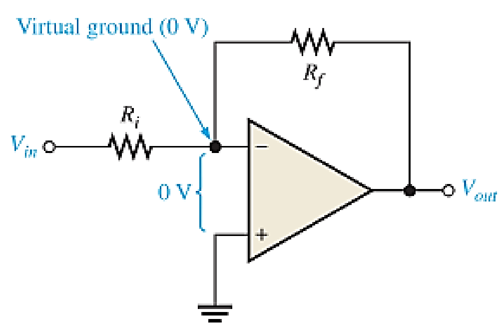
$$A_{cl(VF)} = 1$$



- **Inverting Amplifier**

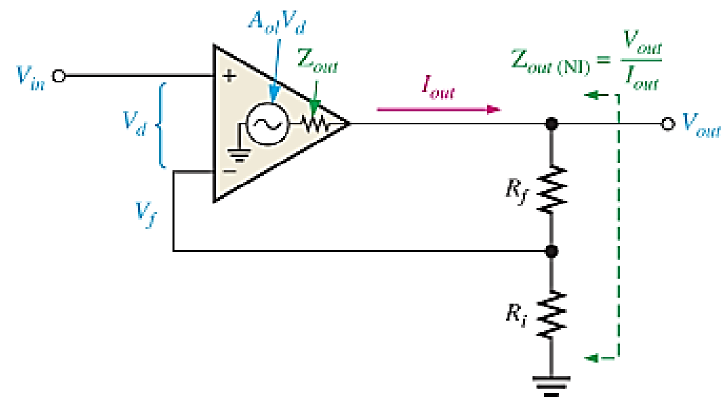
$$A_{cl(I)} = -\frac{R_f}{R_i}$$





EFFECTS OF NEGATIVE FEEDBACK ON OP-AMP IMPEDANCES

- **Non-inverting Amplifier**



$$Z_{in(NI)} = (1 + A_{ol}B)Z_{in}$$

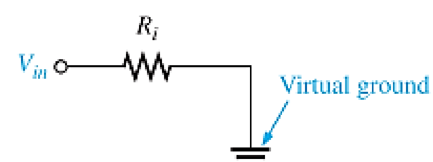
$$Z_{out(NI)} = \frac{Z_{out}}{1 + A_{ol}B}$$

- **Voltage Follower**

$$Z_{in(VF)} = (1 + A_{ol})Z_{in}$$

$$Z_{out(VF)} = \frac{Z_{out}}{1 + A_{ol}}$$

- **Inverting Amplifier**



$$Z_{in(I)} \cong R_i$$

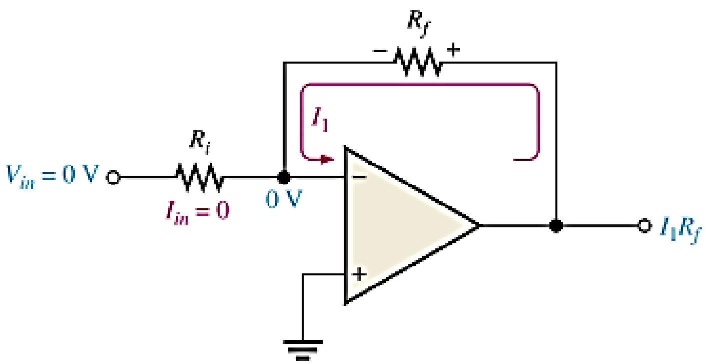
$$Z_{out(I)} = \frac{Z_{out}}{1 + A_{ol}B}$$

Assignment: Derive the impedance equations for Non-inverting and Inverting Amplifiers.

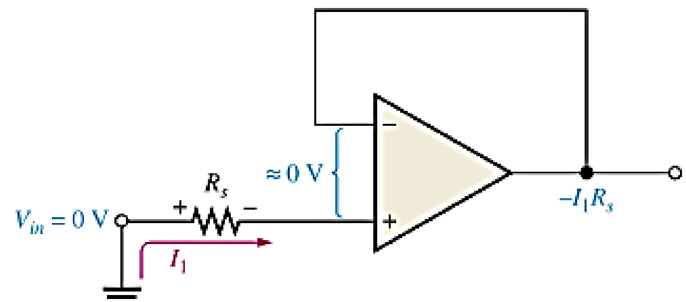
- Certain deviations from the ideal op-amp must be recognized because of their effects on its operation.
- Transistors within the op-amp must be biased so that they have the correct values of base and collector currents and collector-to-emitter voltages.
- The ideal op-amp has no input current at its terminals; but in fact, the practical op-amp has small input bias currents typically in the nA range.
- Also, small internal imbalances in the transistors effectively produce a small offset voltage between the inputs.

BIAS CURRENT AND OFFSET VOLTAGE

Effect of Input Bias Current



(a) Input bias current creates output error voltage (I_1R_f) in an inverting amplifier.



(b) Input bias current creates output error voltage in a voltage-follower.

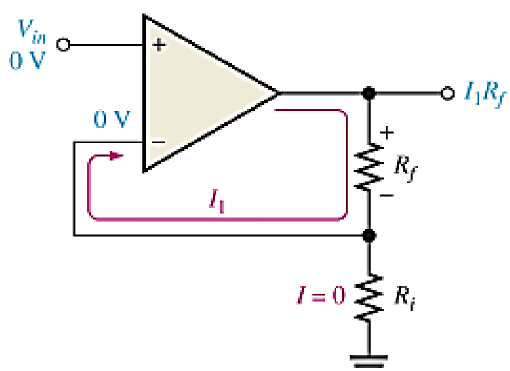
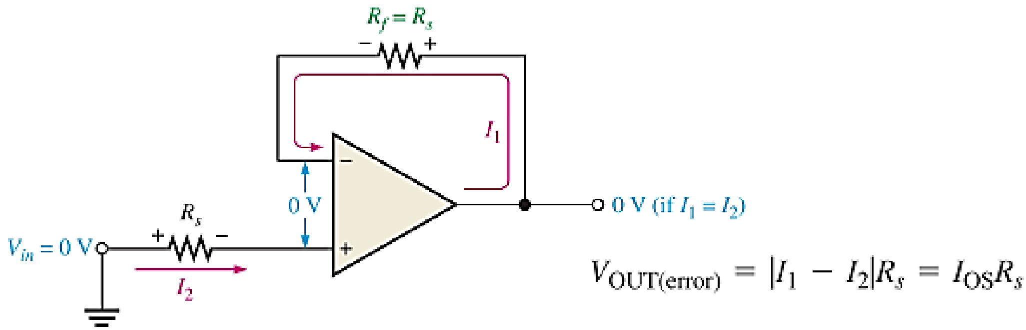
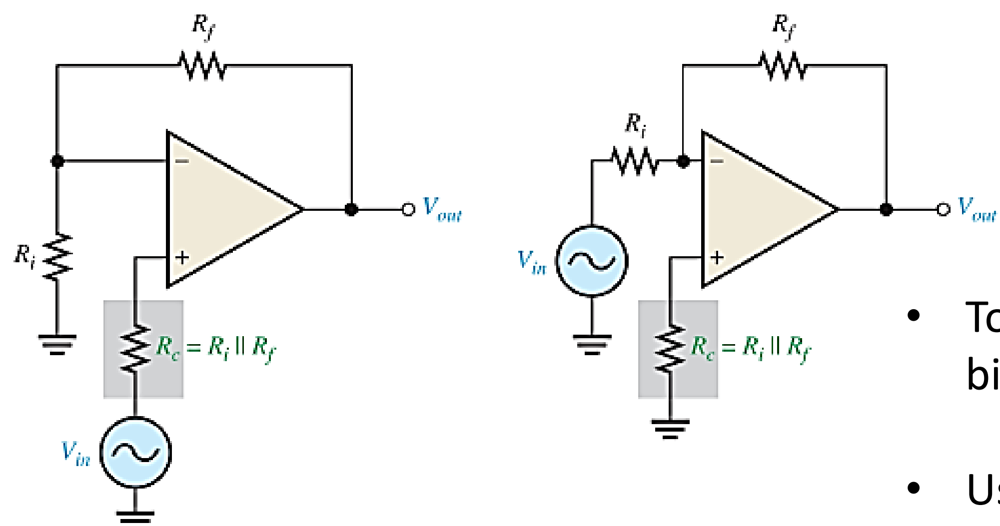


FIGURE 12–30

Input bias current creates output error voltage in a noninverting amplifier.

Bias Current Compensation



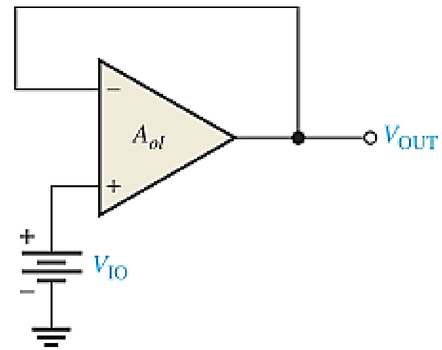


(a) Noninverting amplifier (b) Inverting amplifier

- To compensate for the effect of bias , a resistor Rc is added.
- Use of a BIFET Op-Amp to Eliminate the Need for Bias Current Compensation

Effect of Input Offset Voltage

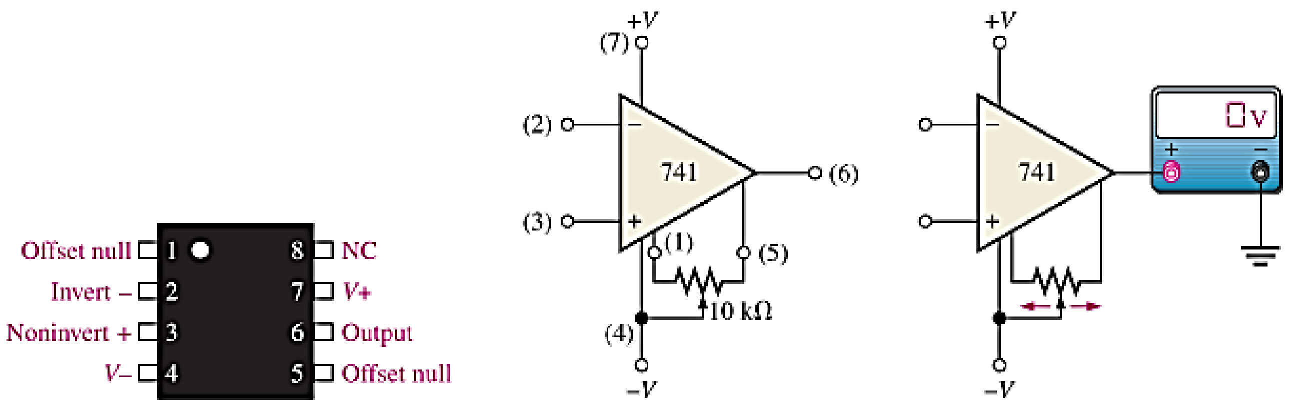
$$V_{OUT(error)} = A_{cl}V_{IO}$$



▲ FIGURE 12–33

Input offset voltage equivalent.

Input Offset Voltage Compensation



(a) 8-pin DIP or SMT package (b) External potentiometer (c) Adjust for zero output

▲ FIGURE 12–34

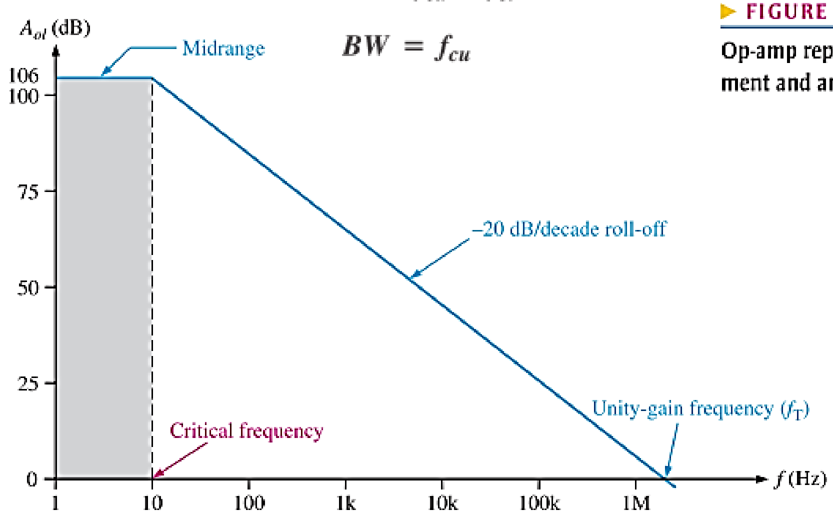
Input offset voltage compensation for a 741 op-amp.

OPEN & CLOSED LOOP FREQUENCY RESPONSES

Open-Loop Frequency & Phase Responses

$$BW = f_{cu} - f_{cl}$$

$$BW = f_{cu}$$

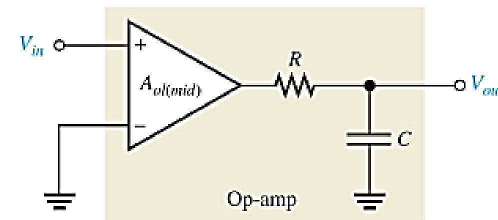


▲ FIGURE 12–36

Ideal plot of open-loop voltage gain versus frequency for a typical op-amp. The frequency scale is logarithmic.

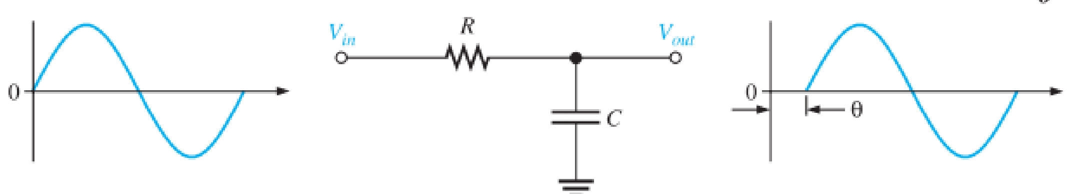
▶ FIGURE 12–38

Op-amp represented by a gain element and an internal *RC* circuit.

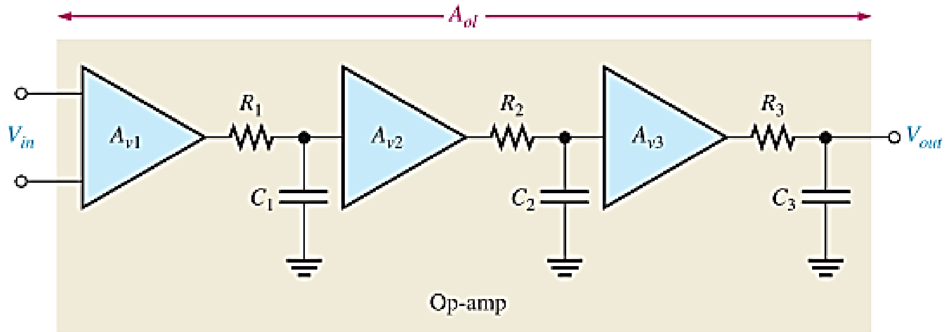


$$A_{ol} = \frac{A_{ol(mid)}}{\sqrt{1 + f^2/f_c^2}}$$

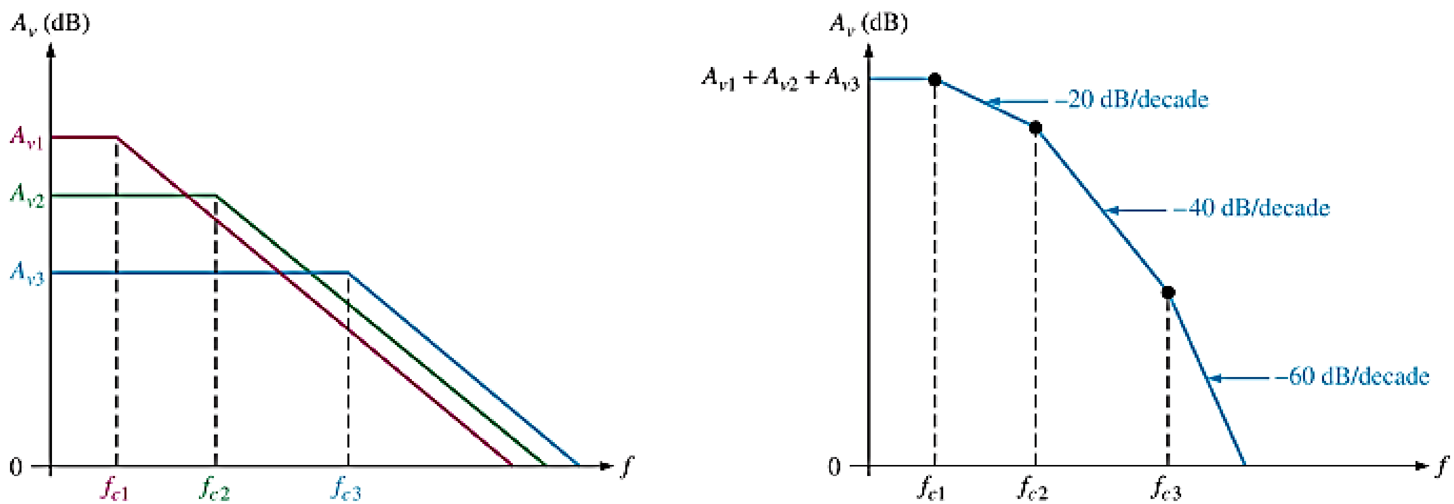
$$\theta = -\tan^{-1}\left(\frac{f}{f_c}\right)$$



Overall Frequency & Phase Responses (Open-Loop)



(a) Representation of an op-amp with three internal stages



(b) Individual responses

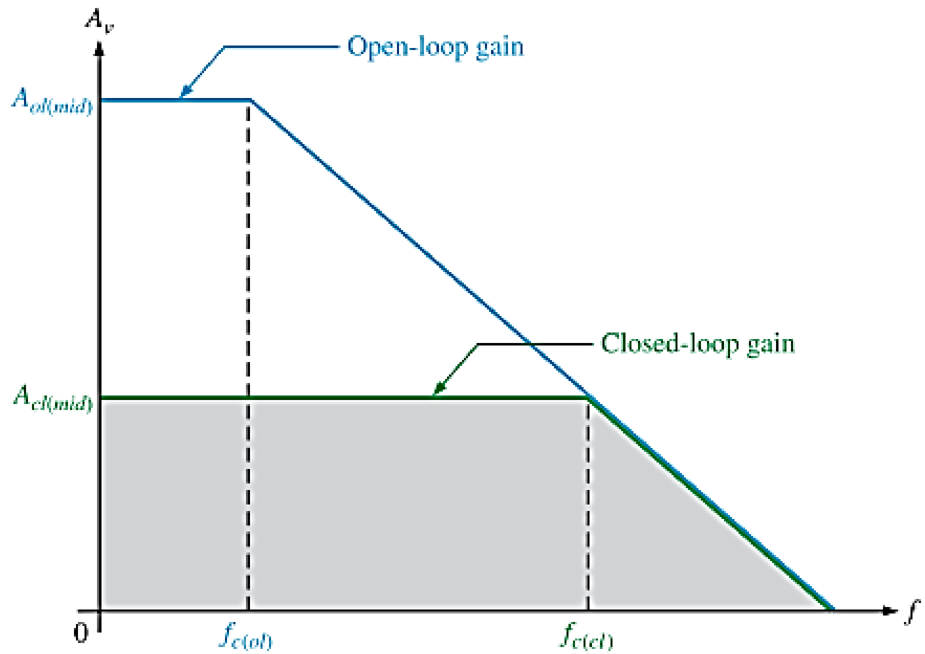
(c) Composite response

$$\theta_{tot} = -\tan^{-1}\left(\frac{f}{f_{c1}}\right) - \tan^{-1}\left(\frac{f}{f_{c2}}\right) - \tan^{-1}\left(\frac{f}{f_{c3}}\right)$$

CLOSED-LOOP FREQUENCY RESPONSE

▶ FIGURE 12–42

Closed-loop gain compared to open-loop gain.



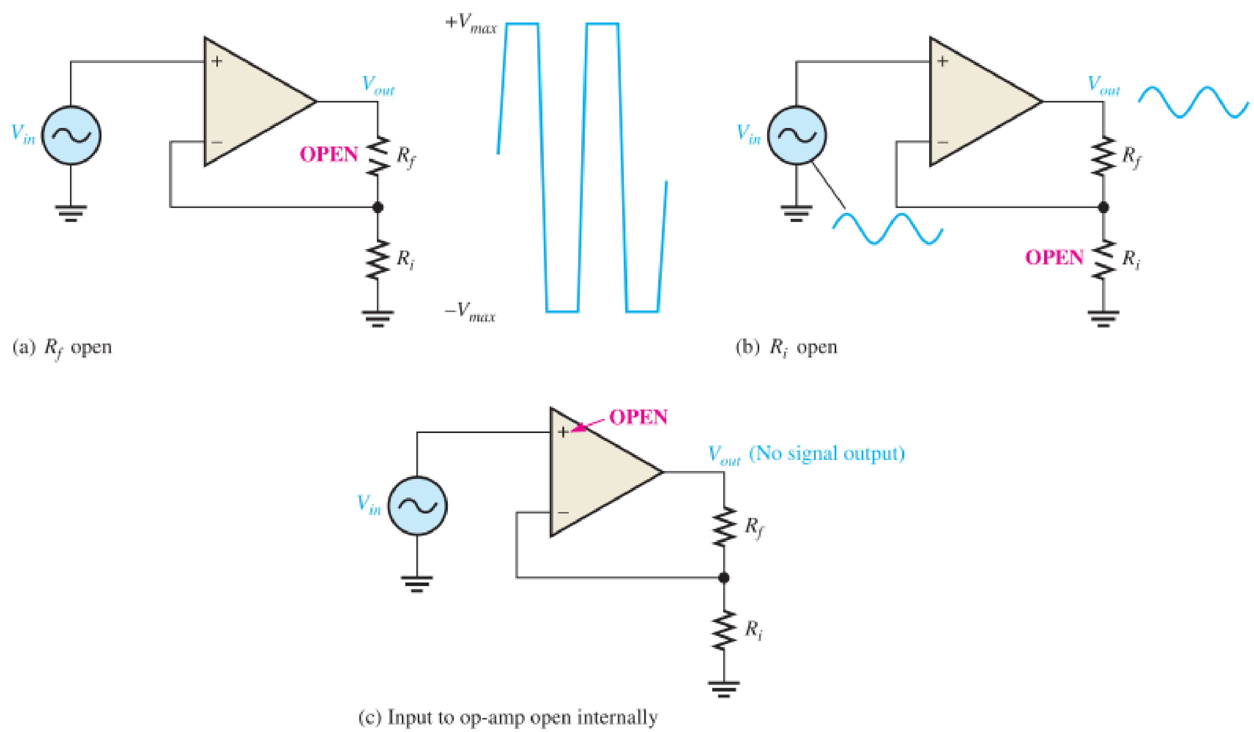
$$f_{c(cl)} = f_{c(ol)}(1 + BA_{ol(mid)})$$

$$BW_{cl} = BW_{ol}(1 + BA_{ol(mid)})$$

- The **gain-bandwidth product** is always equal to the frequency at which the op-amp's open-loop gain is unity or 0 dB (unity-gain bandwidth, f_T).

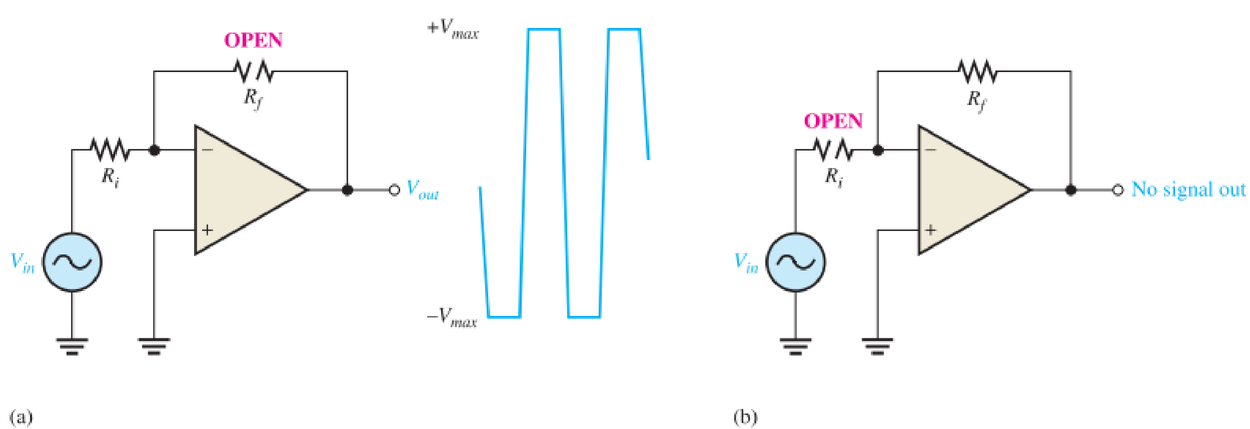
$$f_T = A_{cl} f_{c(cl)}$$

Troubleshooting



▲ FIGURE 12–44

Faults in the noninverting amplifier.



▲ FIGURE 12–45

Faults in the inverting amplifier.

- For more details, refer to:
  - Chapter 12, T. Floyd, **Electronic Devices**, 9th edition.
- The lecture is available online at:
  - http://bu.edu.eg/staff/ahmad.elbanna-courses/12135
- For inquires, send to:
  - ahmad.elbanna@feng.bu.edu.eg