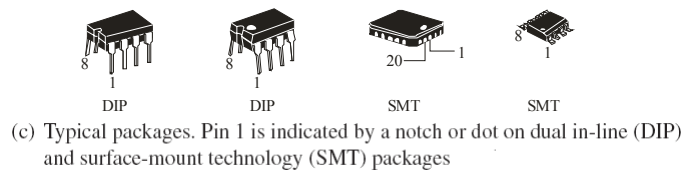
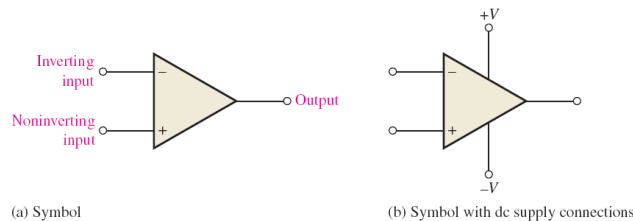


Chapter 12: The Operational Amplifier

12.1: Introduction to Operational Amplifier (Op-Amp)

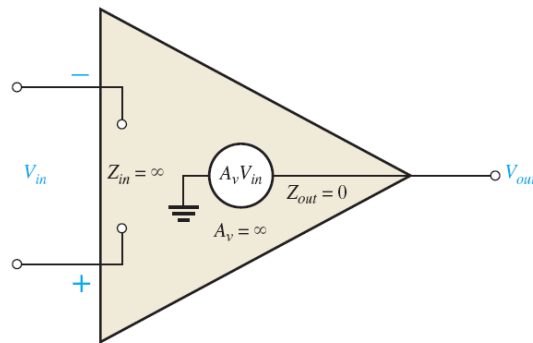
- **Operational amplifiers (op-amps)** are very high gain dc coupled amplifiers with differential inputs; they are used as a voltage controlled voltage sources. One of the inputs is called the inverting input (-); the other is called the noninverting input (+). Usually there is a single output.
- Most op-amps operate with two dc supply voltages, one positive and the other negative, although some have a single dc supply



12.1: Introduction to Operational Amplifier (op-amp)

The Ideal Op-Amp

■ The ideal op-amp has characteristics that simplify analysis of op-amp circuits. Ideally, op-amps have *infinite voltage gain*, *infinite bandwidth*, and *infinite input impedance* → it does not load the driving source. In addition, the ideal op-amp has *zero output impedance*.



(a) Ideal op-amp representation

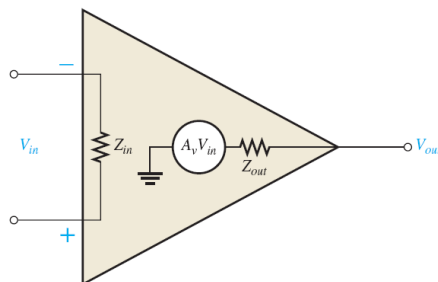
12.1: Introduction to Operational Amplifier (op-amp)

The Practical Op-Amp

■ Practical op-amps have characteristics that often can be treated as ideal for certain situations, but can never actually attain ideal characteristics.

■ Characteristics of a practical op-amp are *very high voltage gain*, *very high input impedance*, and *very low output impedance*

■ In addition to finite gain, bandwidth, input impedance, and noise generation, they have other limitations like voltage and current.



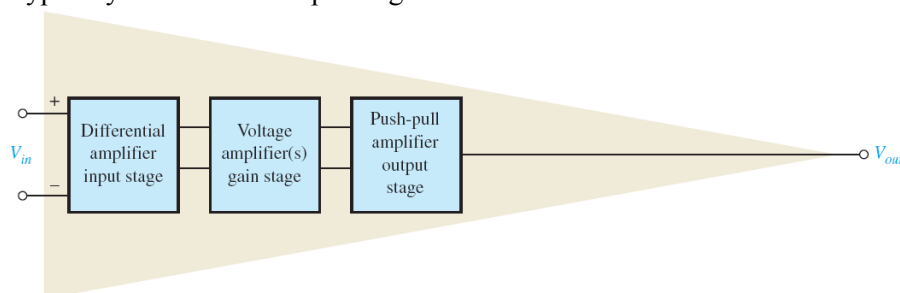
(b) Practical op-amp representation

12.1: Introduction to Operational Amplifier (op-amp)

Internal Block Diagram of an Op-Amp

■ Internally, the typical op-amp has a differential input, a voltage amplifier, and a push-pull output. Recall from the Section 6-7 of the text that the differential amplifier amplifies the *difference* in the two inputs.

■ The **differential amplifier** is the input stage for the op-amp. It provides amplification of the difference voltage between the two inputs. The second stage is usually a class A amplifier (CE amplifier) that provides additional gain. A push-pull class B amplifier (Ch. 7) is typically used for the output stage.



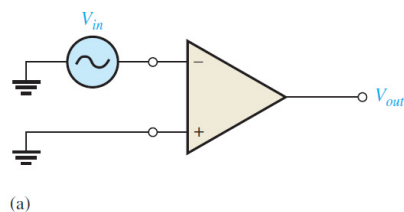
12.2: Op-Amp Input Modes And Parameters

Input Signal Modes

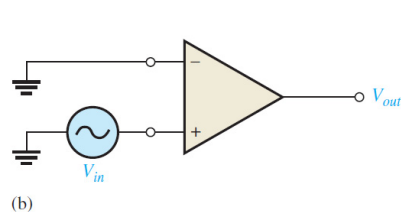
The input signal can be applied to an Op-Amp in differential-mode or in common-mode.

1- Differential Mode: In the single-ended **differential mode**

■ either one signal is applied to an input with the other input grounded



When input signal is applied to inverting input terminal → Inverted output will appear on V_{out}

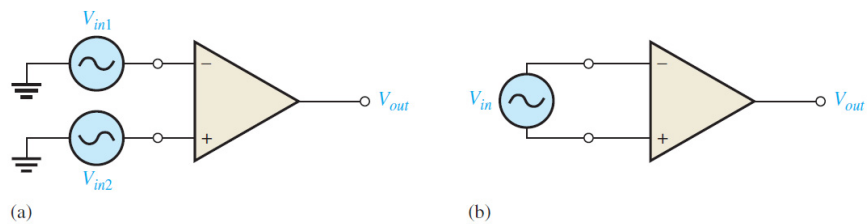


When input signal is applied to inverting input terminal → Non-inverted output will appear on V_{out}

12.2: Op-Amp Input Modes And Parameters

1- Differential Mode: In the double-ended **differential mode**

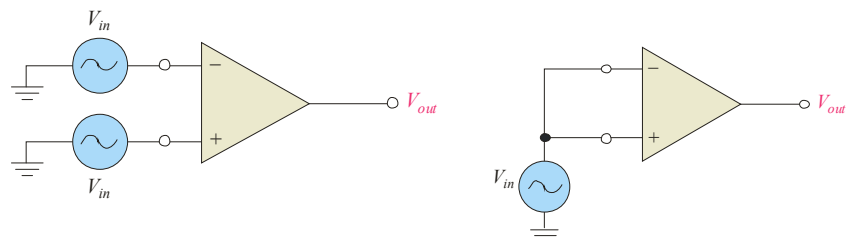
- two opposite-polarity (out of phase) signals are applied to the inputs (figure a); The amplified difference between the two inputs appears on the output
- or a single source connected between the two inputs (figure b)



12.2: Op-Amp Input Modes And Parameters

2- Common Mode:

- two signal voltages of the same phase, frequency, and amplitude are applied to the two inputs, as shown.
- When equal input signals are applied to both inputs, they tend to cancel, resulting in a zero output voltage.



This action is called *common-mode rejection*. Its importance lies in the situation where an unwanted signal appears commonly on both op-amp inputs like noise → unwanted signals will not appear at the output. (usually several thousand)

12.2: Op-Amp Input Modes And Parameters

Op-Amp Parameters

■ **Common-Mode Rejection Ratio (CMRR):** The ability of an amplifier to amplify differential signals and reject common-mode signals (noise appears on both inputs).

■ Ideally, unwanted signals will not appear at the output. However, practical op-amps do exhibit a very small common-mode gain A_{cm} (usually much less than 1), while providing a high open-loop differential voltage gain, A_{ol} (usually several thousand).

■ The ratio of the open-loop differential voltage gain, A_{ol} , to the common-mode gain, A_{cm}

$$\text{CMRR} = \frac{A_{ol}}{A_{cm}}$$

The higher the CMRR, the better

The CMRR is often expressed in decibels (dB) as $\text{CMRR} = 20 \log \left(\frac{A_{ol}}{A_{cm}} \right)$

12.2: Op-Amp Input Modes And Parameters

Op-Amp Parameters

Common-Mode Rejection Ratio (CMRR): Example

A certain op-amp has an open-loop differential voltage gain of 100,000 and a common-mode gain of 0.2. Determine the CMRR and express it in decibels.

$A_{ol} = 100,000$, and $A_{cm} = 0.2$. Therefore,

$$\text{CMRR} = \frac{A_{ol}}{A_{cm}} = \frac{100,000}{0.2} = 500,000$$

This means the desired input signal (differential) is amplified 500,000 times more than the unwanted noise (common-mode).

Expressed in decibels,

$$\text{CMRR} = 20 \log (500,000) = 114 \text{ dB}$$

12.2: Op-Amp Input Modes And Parameters

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 $\pm V_{CC}$.
- practically, $V_{O(p-p)}$ decreases as R_L connected to the op-amp decreases.

■ **Input offset voltage (V_{OS}):** is the differential dc voltage required between the inputs to force the output to zero volts

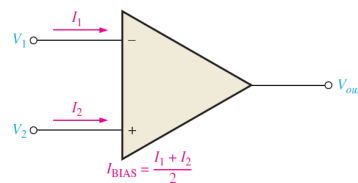
- The ideal op-amp produces zero volts out for zero volts in.
- In a practical op-amp, a small dc voltage, $V_{OUT(error)}$, appears at the output when no differential input voltage is applied \rightarrow we apply V_{OS} ; typical input offset voltage are in the range of 2 mV or less

12.2: Op-Amp Input Modes And Parameters

Op-Amp Parameters

■ **Input bias current (I_{BIAS}):** is the average of the two dc currents required to bias the bases of differential amplifier

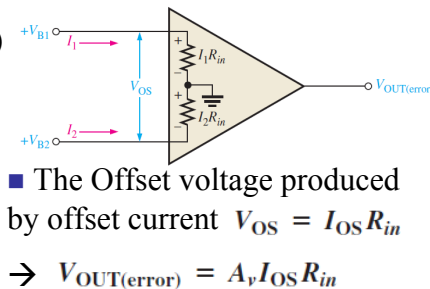
$$I_{BIAS} = \frac{I_1 + I_2}{2}$$



■ **input offset current (I_{OS}):** is the difference between the two dc bias currents

$$I_{OS} = |I_1 - I_2| \text{ (usually neglected)}$$

- 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.

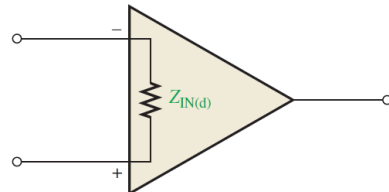


12.2: Op-Amp Input Modes And Parameters

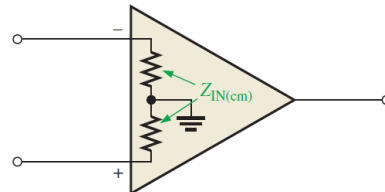
Op-Amp Parameters

■ **Differential input impedance ($Z_{IN(d)}$):** The is the total resistance between the inputs

■ **Common-mode input impedance ($Z_{IN(cm)}$):** The is the resistance between each input and ground

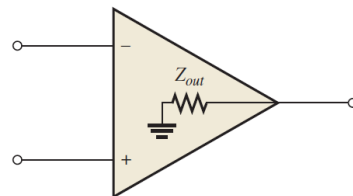


(a) Differential input impedance



(b) Common-mode input impedance

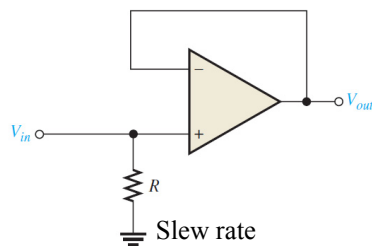
■ **Output impedance (Z_{out}):** The is the resistance viewed from the output of the circuit.



12.2: Op-Amp Input Modes And Parameters

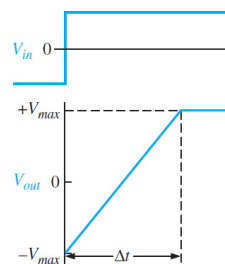
Op-Amp Parameters

■ **Slew rate:** is the maximum rate of change of the output voltage in response to a step input voltage



(a) Test circuit

Slew rate
measuring circuit



(b) Step input voltage and the resulting output voltage

$$\text{Slew rate} = \frac{\Delta V_{out}}{\Delta t} \quad \text{where } \Delta V_{out} = +V_{max} - (-V_{max})$$

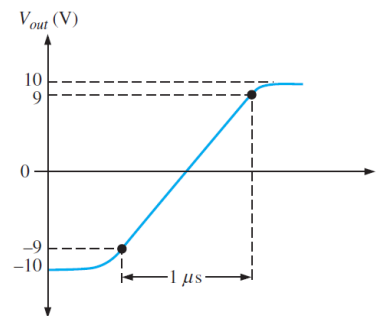
12.2: Op-Amp Input Modes And Parameters

Op-Amp Parameters

Slew rate: Example

The output voltage of a certain op-amp appears as shown in Figure in response to a step input. Determine the slew rate.

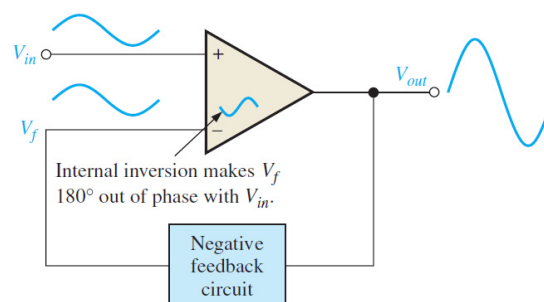
$$\begin{aligned}\text{Slew rate} &= \frac{\Delta V_{out}}{\Delta t} \\ &= \frac{+9 \text{ V} - (-9 \text{ V})}{1 \mu\text{s}} = 18 \text{ V}/\mu\text{s}\end{aligned}$$



12.3: Negative feedback

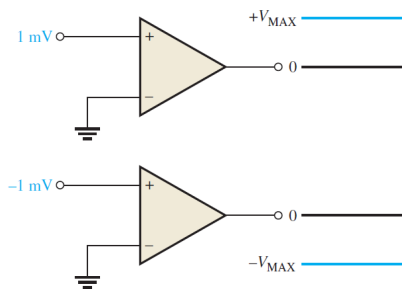
Negative feedback is one of the most useful concepts in op-amp applications

- **Negative feedback** is the process of returning a portion of the output signal to the input with a phase angle that opposes the input signal (to the inverting output).
- → The advantage of negative feedback is that precise values of amplifier gain can be set. In addition, bandwidth and input and output impedances can be controlled.



12.3: Negative feedback

■ Why? The open-loop voltage gain of a typical op-amp is very high → an extremely small input voltage drives the op-amp into its saturated output states (for A_{ol} of 100000, 1mv input has amplified value of 100V which is very high from the operating voltage of op-amp → amplifier is driven into saturation → nonlinear operation.



	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

12.4: Op-Amp with Negative feedback

■ An op-amp can be connected using negative feedback (closed-loop) to stabilize the gain (much lower gain than opened-loop) and increase frequency response.

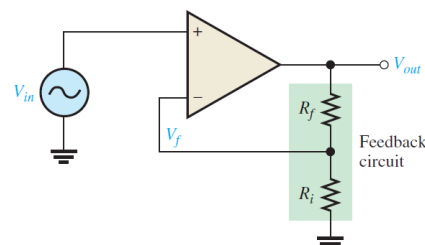
Noninverting Amplifier

■ A **noninverting amplifier** is a configuration in which the input signal is applied on the noninverting input and a portion of the output is returned (feedback) to the inverting input → V_{out} will be reduced by R_i , R_f , and hence by V_f

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

→ There will be feedback attenuation, B, for V_{out} precisely decided by R_i and R_f according to

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



12.4: Op-Amp with Negative feedback

■ Hence, V_{out} will be the amplified differential input between V_{in} and V_f

$$\rightarrow V_{out} = A_{ol}(V_{in} - V_f) = A_{ol}(V_{in} - BV_{out})$$

$$V_{out} = A_{ol}V_{in} - A_{ol}BV_{out}$$

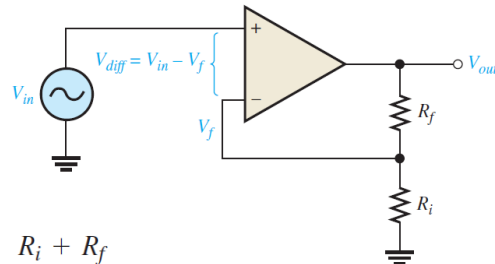
$$\rightarrow \frac{V_{out}}{V_{in}} = \frac{A_{ol}}{1 + A_{ol}B}$$

$A_{ol}B$ is typically $\gg 1$

$$\rightarrow A_{cl(NI)} = \frac{V_{out}}{V_{in}} \cong \frac{A_{ol}}{A_{ol}B} = \frac{1}{B} = \frac{R_i + R_f}{R_i}$$

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

The **closed-loop noninverted (NI) voltage gain**; noninverted voltage gain of an op-amp with external feedback



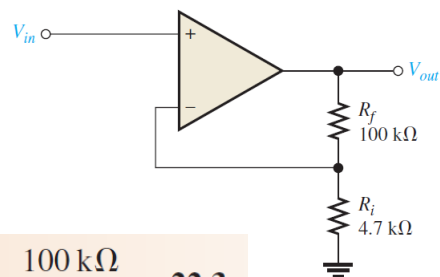
12.4: Op-Amp with Negative feedback

Noninverting Amplifier: Example

Determine the closed-loop voltage gain of the amplifier in Figure

We have a noninverting op-amp configuration

$$\rightarrow A_{cl(NI)} = 1 + \frac{R_f}{R_i} = 1 + \frac{100 \text{ k}\Omega}{4.7 \text{ k}\Omega} = 22.3$$

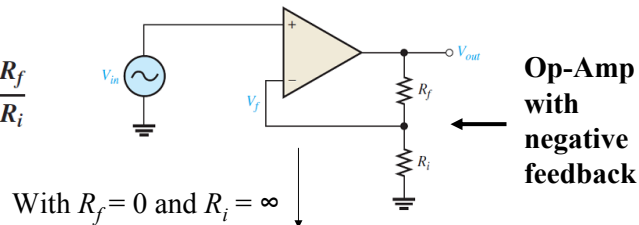


12.4: Op-Amp with Negative feedback

Voltage-Follower

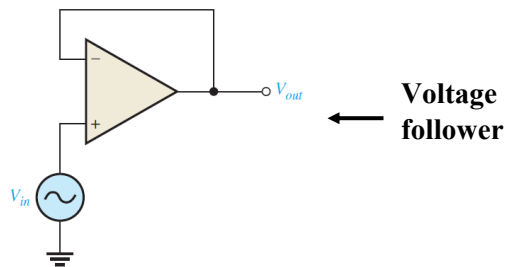
■ Voltage follower is a special case of the inverting amplifier is when $R_f = 0$ and $R_i = \infty$.

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



■ This forms a voltage follower or unity gain buffer with a gain of 1.

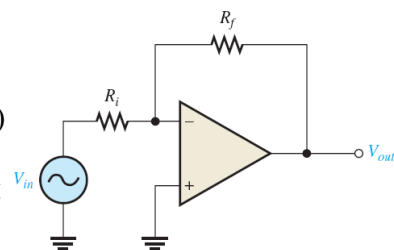
$$A_{cl(VF)} = 1$$



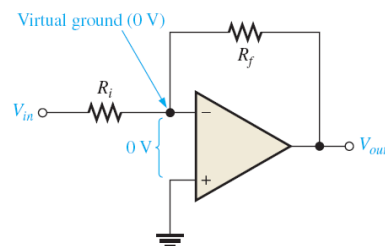
12.4: Op-Amp with negative feedback

Inverting Amplifier

■ An **inverting amplifier** shown is a configuration in which The noninverting (+) input is grounded and the input signal is applied through a resistor R_i to the inverting input (-). Also, the output is fed back through R_f to the same input.



■ Since $Z_{in} = \infty \rightarrow I_1$ through $Z_{in} = 0 \rightarrow V_{Z_{in}} = 0$. Hence the (-) input has voltage = the (+) input voltage = the ground voltage = 0 V \rightarrow the (-) input is called virtual ground



(a) Virtual ground

12.4: Op-Amp with negative feedback

Inverting Amplifier

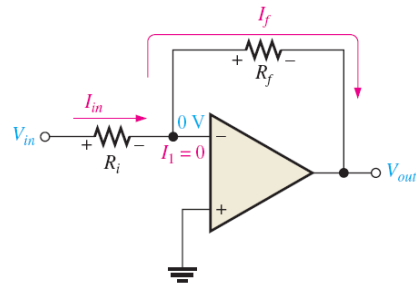
■ Since I_1 through $Z_{in} = 0 \rightarrow$ current through R_i = current through R_f

$$I_f = I_{in} \rightarrow \frac{-V_{out}}{R_f} = \frac{V_{in}}{R_i}$$

$$\rightarrow \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_i}$$

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

Closed loop voltage gain of the inverting amplifier

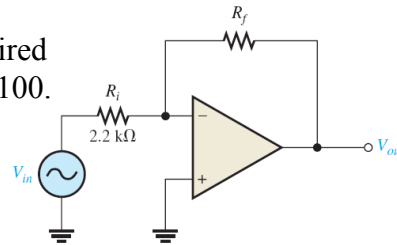


(b) $I_{in} = I_f$ and current at the inverting input (I_1) is 0.

Example: determine the value of R_f required to produce a closed-loop voltage gain of 100.

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

$$R_f = |A_{cl(I)}| R_i = (100)(2.2 \text{ k}\Omega) = 220 \text{ k}\Omega$$



12.5: Effect of Negative Feedback on Op-Amp Impedances

Impedances of the Noninverting Amplifier: Input Impedance

$$V_{in} = V_d + V_f = V_d + B V_{out}$$

$$\text{Since } V_{out} \cong A_{ol} V_d$$

$$\rightarrow V_{in} = V_d + A_{ol} B V_d = (1 + A_{ol} B) V_d$$

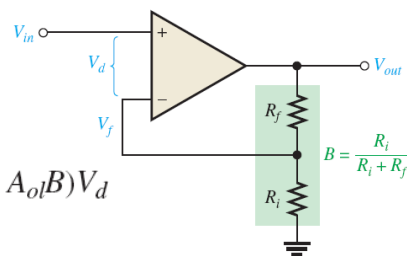
$$\text{substituting } I_{in} Z_{in} \text{ for } V_d \rightarrow V_{in} = (1 + A_{ol} B) I_{in} Z_{in}$$

$$\text{Rearrange } \rightarrow \frac{V_{in}}{I_{in}} = (1 + A_{ol} B) Z_{in}$$

$$\text{Hence, } Z_{in(NI)} = (1 + A_{ol} B) Z_{in}$$

overall input impedance of a closed-loop noninverting amplifier

Hence, with negative feedback $\rightarrow Z_{in(NI)} \gg Z_{in} \text{ (without feedback)}$



12.5: Effect of Negative Feedback on Op-Amp Impedances

Impedances of the Noninverting Amplifier: Output Impedance

The output circuit is shown in the figure

Applying KVL from V_{out} to the ground through Z_{out} →

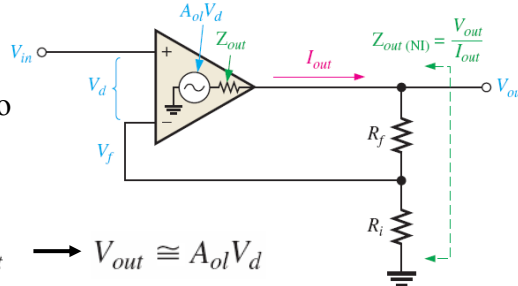
$$V_{out} = A_{ol}V_d - Z_{out}I_{out}$$

$$\text{assume } A_{ol}V_d \gg Z_{out}I_{out} \rightarrow V_{out} \cong A_{ol}V_d$$

With some algebra one can show that (SEE TEXT BOOK)

$$Z_{out(NI)} = \frac{Z_{out}}{1 + A_{ol}B} \quad \text{output impedance of a closed-loop noninverting amplifier}$$

$$(Z_{out(NI)} \ll Z_{out})$$



12.5: Effect of Negative Feedback on Op-Amp Impedances

Impedances of the Noninverting Amplifier: Example

(a) Determine the input and output impedances of the amplifier in Figure 12–25. The op-amp datasheet gives $Z_{in} = 2 \text{ M}\Omega$, $Z_{out} = 75 \text{ }\Omega$, and $A_{ol} = 200,000$.

(b) Find the closed-loop voltage gain.

(a) The attenuation, B , of the feedback circuit is

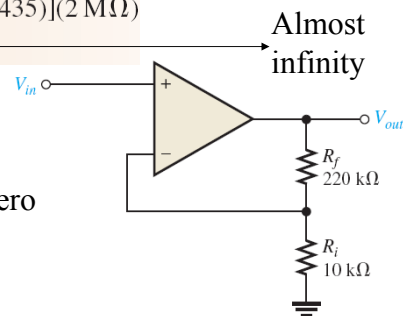
$$B = \frac{R_i}{R_i + R_f} = \frac{10 \text{ k}\Omega}{230 \text{ k}\Omega} = 0.0435$$

$$Z_{in(NI)} = (1 + A_{ol}B)Z_{in} = [1 + (200,000)(0.0435)](2 \text{ M}\Omega) \\ = (1 + 8700)(2 \text{ M}\Omega) = \mathbf{17.4 \text{ G}\Omega}$$

$$Z_{out(NI)} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{75 \text{ }\Omega}{1 + 8700} = \mathbf{8.6 \text{ m}\Omega}$$

Almost zero

$$(b) A_{cl(NI)} = 1 + \frac{R_f}{R_i} = 1 + \frac{220 \text{ k}\Omega}{10 \text{ k}\Omega} = \mathbf{23.0}$$



12.5: Effect of Negative Feedback on Op-Amp Impedances

Voltage-Follower Impedances

The special case of noninverting Op-Amp with $B=1$ has impedances of

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

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

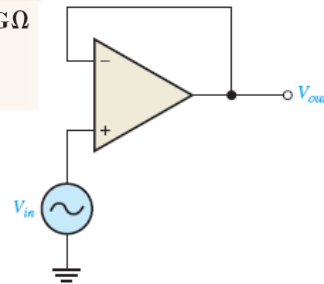
Determine the input and output impedances of the amplifier in Figure op-amp datasheet gives $Z_{in} = 2 \text{ M}\Omega$, $Z_{out} = 75 \Omega$, and $A_{ol} = 200,000$.

This is a voltage follower configuration

Since $B = 1$,

$$Z_{in(VF)} = (1 + A_{ol})Z_{in} = (1 + 200,000)(2 \text{ M}\Omega) \cong 400 \text{ G}\Omega$$

$$Z_{out(VF)} = \frac{Z_{out}}{1 + A_{ol}} = \frac{75 \Omega}{1 + 200,000} = 375 \mu\Omega$$



12.5: Effect of Negative Feedback on Op-Amp Impedances

Impedances of the Inverting Amplifier

■ The input impedance is the impedance between input and the virtual ground

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

■ The output impedance is same as for noninverting OP-Amp

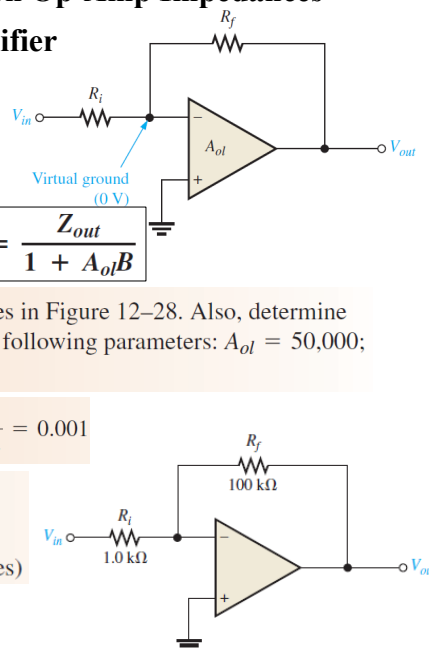
$$Z_{out(I)} = \frac{Z_{out}}{1 + A_{ol}B}$$

Find the values of the input and output impedances in Figure 12-28. Also, determine the closed-loop voltage gain. The op-amp has the following parameters: $A_{ol} = 50,000$; $Z_{in} = 4 \text{ M}\Omega$; and $Z_{out} = 50 \Omega$.

$$Z_{in(I)} \cong R_i = 1.0 \text{ k}\Omega \quad B = \frac{R_i}{R_i + R_f} = \frac{1.0 \text{ k}\Omega}{101 \text{ k}\Omega} = 0.001$$

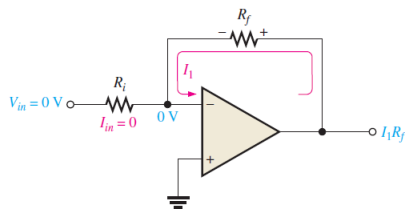
$$Z_{out(I)} = \frac{Z_{out}}{1 + A_{ol}B} = \frac{50 \Omega}{1 + (50,000)(0.001)} = 980 \text{ m}\Omega \text{ (zero for all practical purposes)}$$

$$A_{cl(I)} = -\frac{R_f}{R_i} = -\frac{100 \text{ k}\Omega}{1.0 \text{ k}\Omega} = -100$$

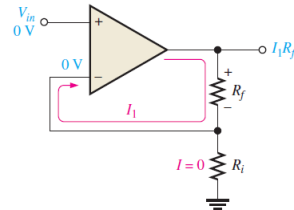


12.6: Bias Current and Offset Voltage

■ With zero input voltage ($V_{in} = 0$), the ideal op-amp has no input current at its terminals; but in fact, the practical op-amp has small input bias currents, due to dc biasing voltages, typically in the nA range. Also, small internal imbalances in the transistors effectively produce a small offset voltage between the inputs (V_{IO}) \rightarrow error in the output voltage ($V_{out(error)}$) will be produced as a result



Input bias current creates output error voltage ($I_1 R_f$) in an inverting amplifier.



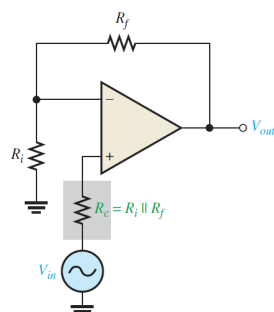
Input bias current creates output error voltage ($I_1 R_f$) in a noninverting amplifier.

12.6: Bias Current and Offset Voltage

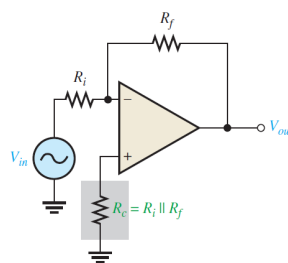
Bias Current Compensation

To compensate for the small output error voltage, a resistor R_c equal to $R_i \parallel R_f$ is added to one of the inputs. R_c create current at the other input $\rightarrow \Delta I$ at the inputs = 0, and hence no offset voltage V_{IO} between inputs \rightarrow no $V_{out(error)}$ during op amp operation.

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



(a) Noninverting amplifier

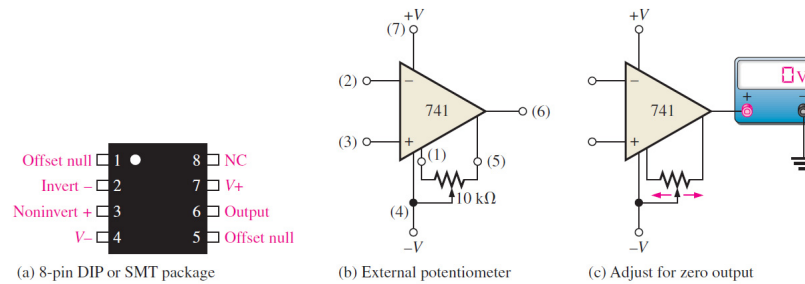


(b) Inverting amplifier

12.6: Bias Current and Offset Voltage

Input offset voltage Compensation

Most integrated circuit op-amps provide an internally means of compensating for offset voltage. This is usually done by connecting an external potentiometer to designated pins (Offset null) on the IC package, the potentiometer is adjusted until the output is zero



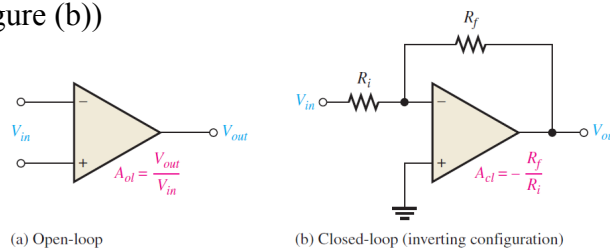
12.7: Open-Loop Frequency and Phase Response

■ Open-loop responses relate to an op-amp with no external feedback. The frequency response indicates how the voltage gain changes with frequency, and the phase response indicates how the phase shift between the input and output signal changes with frequency

Review of Op-Amp Voltage Gains

■ The open-loop voltage gain, A_{ol} , of an op-amp is the internal voltage gain of the device and represents the ratio of output voltage to input voltage with no external components (Figure (a))

■ The closed-loop voltage gain, A_{cl} , is the voltage gain of an op-amp with external feedback. It is controlled by the external components value (Figure (b))



12.7: Open-Loop Frequency and Phase Response

Bandwidth Limitations

- Op-amps has no lower critical frequency, f_{cl} (no capacitive coupling between stages inside the op-amp) → the midrange gain extends down to zero frequency (dc), and dc voltages are amplified the same as midrange signal frequencies → they are called dc amplifiers.
- The voltage gain described before (open-loop and closed-loop) are voltage gains at midrange frequency.
- Roll-off (-20dB/decade or -6dB/octave) of voltage gain (due to the internal transistor capacitors) begins at upper critical frequency f_c , where the voltage gain is -3dB from the midrange voltage gain → The bandwidth is

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

Sine For op-amp with $f_{cl} = 0$ → the band width will be equal to upper critical frequency

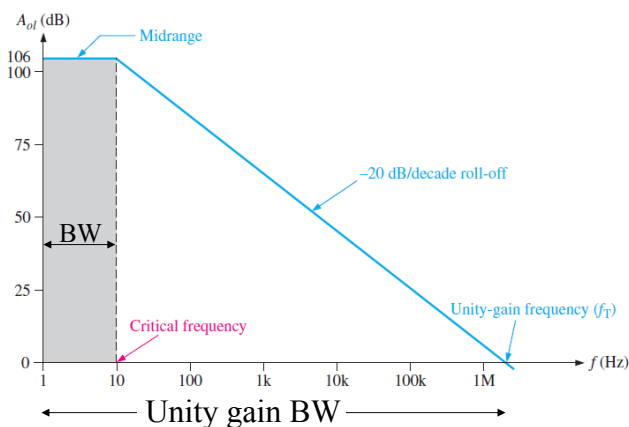
$$BW = f_{cu}$$

- Roll-off of voltage gain continue until reaching the point where the voltage gain is equal to unity (1 or 0dB) at *unity-gain frequency* (or *unity gain bandwidth*), f_T .

12.7: Open-Loop Frequency and Phase Response

Bandwidth Limitations

- As an example, An open-loop response curve (Bode plot) for a certain op-amp is shown in Figure below usually specified by op-amp datasheets. The curve rolls off (decreases) at -20dB/decade (-6dB/per octave). The midrange gain is 200,000 (106 dB), and the critical (cutoff) frequency is approximately 10 Hz.



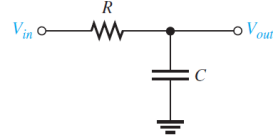
12.7: Open-Loop Frequency and Phase Response

Gain-Versus-Frequency Analysis

■ The RC lag (low-pass) circuits (represented by the circuit shown) within an op-amp are responsible for the roll-off in gain as the frequency increases

The attenuation of the RC lag circuit is

$$\frac{V_{out}}{V_{in}} = \frac{X_C}{\sqrt{R^2 + X_C^2}} = \frac{1}{\sqrt{1 + R^2/X_C^2}}$$



The critical frequency of an

RC circuit is at $C = R \rightarrow f_c = \frac{1}{2\pi RC}$

RC lag (تأخير) circuit

Dividing both sides by $f \rightarrow \frac{f_c}{f} = \frac{1}{2\pi RCf} = \frac{1}{(2\pi fC)R} = \frac{X_C}{R} \rightarrow \frac{f_c}{f} = \frac{X_C}{R}$

Hence the attenuation due to RC lag circuit is

$$\frac{V_{out}}{V_{in}} = \frac{1}{\sqrt{1 + f^2/f_c^2}}$$

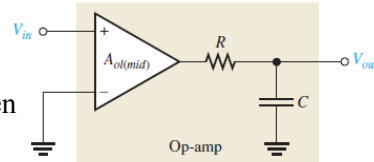
12.7: Open-Loop Frequency and Phase Response

Gain-Versus-Frequency Analysis

■ If an op-amp is represented by a voltage gain element with a gain of $A_{ol(mid)}$ plus a single RC lag circuit, as shown in Figure, then

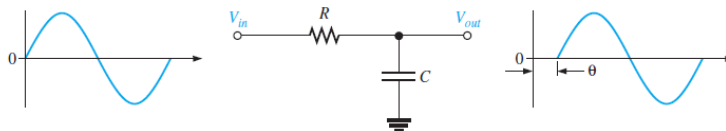
The total open-loop gain of the op-amp is

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



Phase Shift: An RC lag circuit such as found in an op-amp stage causes the output signal voltage to lag the input (we can add -ve sign) with phase shift $\theta \rightarrow \theta = -\tan^{-1}\left(\frac{R}{X_C}\right)$

Since $R/X_C = f/f_c \rightarrow \theta = -\tan^{-1}\left(\frac{f}{f_c}\right)$



12.7: Open-Loop Frequency and Phase Response

Gain-Versus-Frequency Analysis : Example

Determine A_{ol} for the following values of f . Assume $f_{c(ol)} = 100$ Hz and $A_{ol(mid)} = 100,000$.

- (a) $f = 0$ Hz (b) $f = 10$ Hz (c) $f = 100$ Hz (d) $f = 1000$ Hz

Solution (a) $A_{ol} = \frac{A_{ol(mid)}}{\sqrt{1 + f^2/f_{c(ol)}^2}} = \frac{100,000}{\sqrt{1 + 0}} = 100,000$

(b) $A_{ol} = \frac{100,000}{\sqrt{1 + (0.1)^2}} = 99,503$

(c) $A_{ol} = \frac{100,000}{\sqrt{1 + (1)^2}} = \frac{100,000}{\sqrt{2}} = 70,710$

(d) $A_{ol} = \frac{100,000}{\sqrt{1 + (10)^2}} = 9950$

12.7: Open-Loop Frequency and Phase Response

Phase shift : Example

Calculate the phase shift for an RC lag circuit for each of the following frequencies, and then plot the curve of phase shift versus frequency. Assume $f_c = 100$ Hz.

- (a) $f = 1$ Hz (b) $f = 10$ Hz (c) $f = 100$ Hz
(d) $f = 1000$ Hz (e) $f = 10,000$ Hz

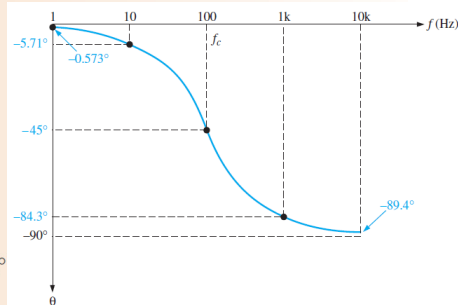
Solution (a) $\theta = -\tan^{-1}\left(\frac{f}{f_c}\right) = -\tan^{-1}\left(\frac{1 \text{ Hz}}{100 \text{ Hz}}\right) = -0.573^\circ$

(b) $\theta = -\tan^{-1}\left(\frac{10 \text{ Hz}}{100 \text{ Hz}}\right) = -5.71^\circ$

(c) $\theta = -\tan^{-1}\left(\frac{100 \text{ Hz}}{100 \text{ Hz}}\right) = -45^\circ$

(d) $\theta = -\tan^{-1}\left(\frac{1000 \text{ Hz}}{100 \text{ Hz}}\right) = -84.3^\circ$

(e) $\theta = -\tan^{-1}\left(\frac{10,000 \text{ Hz}}{100 \text{ Hz}}\right) = -89.4^\circ$

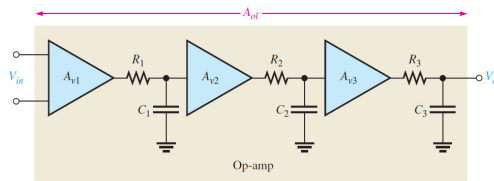


The phase shift-versus-frequency curve is plotted in Figure 12–40. Note that the frequency axis is logarithmic.

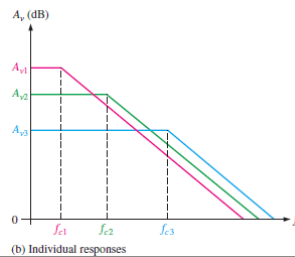
12.7: Open-Loop Frequency and Phase Response

Overall Frequency Response

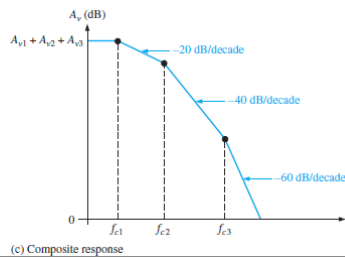
■ The more complex IC operational amplifier may consist of two or more cascaded amplifier stages → total voltage gain at mid range is the algebraic addition of dB gain for each stage. Also the phase between output and input is the addition of phase angles for each stage



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



(b) Individual responses



(c) Composite response

Note the roll-off for the three stages shown

12.7: Open-Loop Frequency and Phase Response

Overall Frequency Response: Example

A certain op-amp has three internal amplifier stages with the following gains and critical frequencies:

Stage 1: $A_{v1} = 40 \text{ dB}$, $f_{c1} = 2 \text{ kHz}$

Stage 2: $A_{v2} = 32 \text{ dB}$, $f_{c2} = 40 \text{ kHz}$

Stage 3: $A_{v3} = 20 \text{ dB}$, $f_{c3} = 150 \text{ kHz}$

Determine the open-loop midrange gain in decibels and the total phase lag when $f = f_{c1}$.

$$A_{ol(mid)} = A_{v1} + A_{v2} + A_{v3} = 40 \text{ dB} + 32 \text{ dB} + 20 \text{ dB} = 92 \text{ dB}$$

$$\begin{aligned} \theta_{tot} &= -\tan^{-1}\left(\frac{f}{f_{c1}}\right) - \tan^{-1}\left(\frac{f}{f_{c2}}\right) - \tan^{-1}\left(\frac{f}{f_{c3}}\right) \\ &= -\tan^{-1}(1) - \tan^{-1}\left(\frac{2}{40}\right) - \tan^{-1}\left(\frac{2}{150}\right) = -45^\circ - 2.86^\circ - 0.76^\circ = -48.6^\circ \end{aligned}$$

12.7: Closed-Loop Frequency and Phase Response

■ The midrange gain of an op-amp is reduced by negative feedback, as indicated by the following closed-loop gain expressions for the three amplifier

For a noninverting amplifier, $A_{cl(NI)} = 1 + \frac{R_f}{R_i}$

For an inverting amplifier, $A_{cl(I)} \cong -\frac{R_f}{R_i}$

For a voltage-follower, $A_{cl(VF)} = 1$

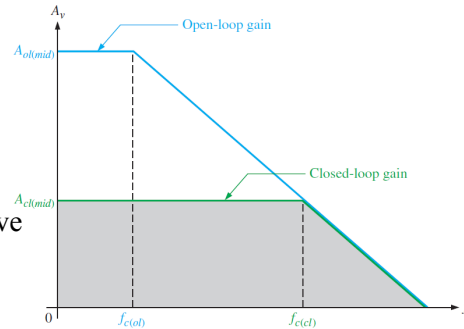
■ Since feedback affect the gain and impedances → critical frequency will also be affected → The closed-loop critical frequency of an op-amp with –ve feedback will increase according to

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

Since $f_{c(ol)}$ equals the bandwidth → the bandwidth for the closed-loop amplifier will also increased by the same factor

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

■ Hence, with feedback we have lower voltage gain and higher BW as shown



12.7: Closed-Loop Frequency and Phase Response

Example

A certain amplifier has an open-loop midrange gain of 150,000 and an open-loop 3 dB bandwidth of 200 Hz. The attenuation (B) of the feedback loop is 0.002. What is the closed-loop bandwidth?

Solution $BW_{cl} = BW_{ol}(1 + BA_{ol(mid)}) = 200 \text{ Hz}[1 + (0.002)(150,000)] = 60.2 \text{ kHz}$

Gain-Bandwidth Product

■ As long as the roll-off rate is fixed, a decrease in closed-loop gain causes an increase in the bandwidth and vice versa, such that the product of gain and bandwidth is a constant

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

Since the product of midrange gain and bandwidth always equal to frequency of unity gain as shown in chapter 10 ($f_T = A_{v(mid)}BW$)

→ For closed loop, the unity gain frequency f_T will be

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