Operational Amplifiers

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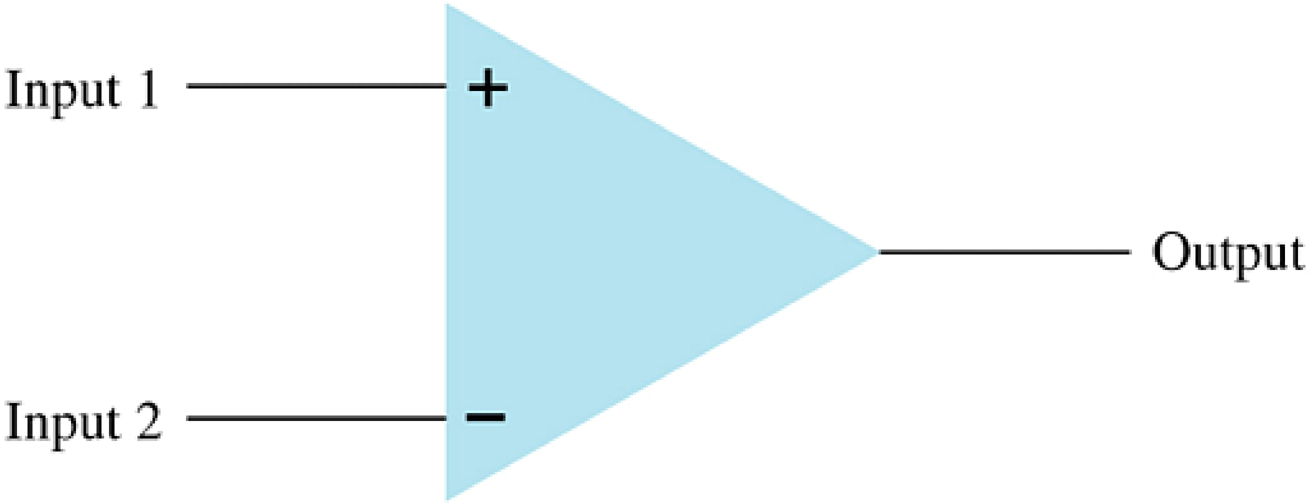
Introduction



Operational amplifier or op-amp, is a very high gain differential amplifier with a high input impedance and low output impedance.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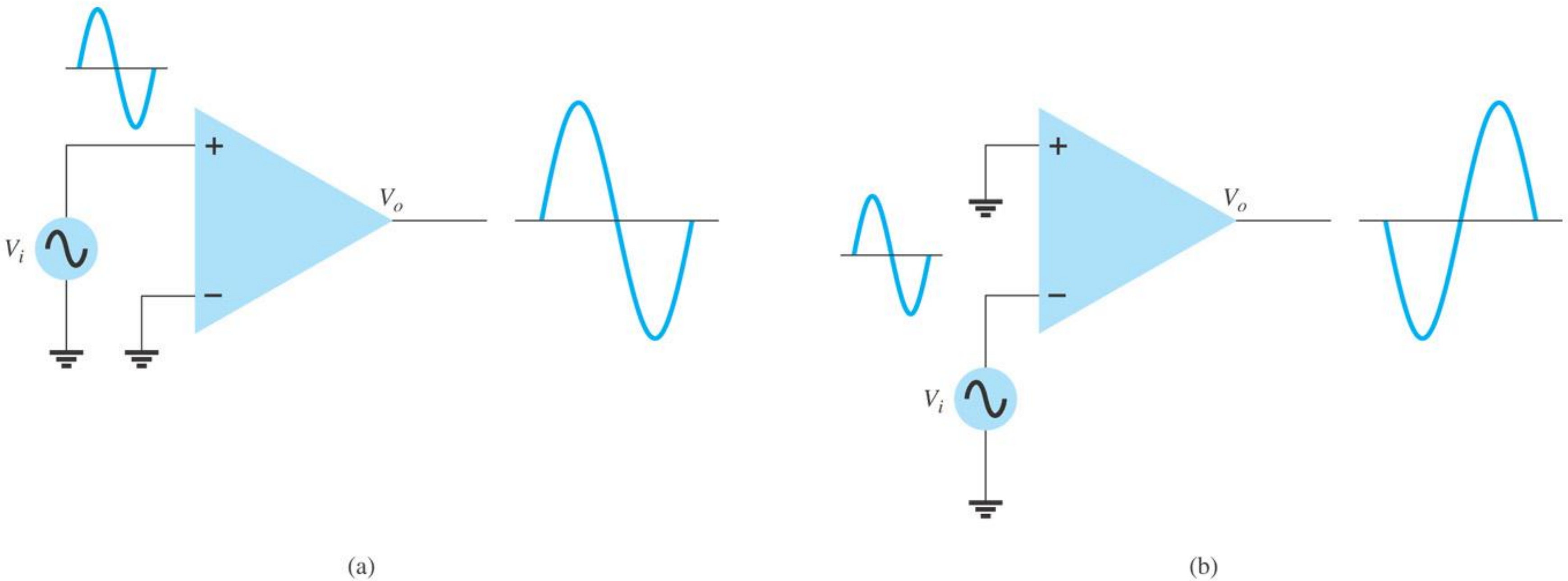
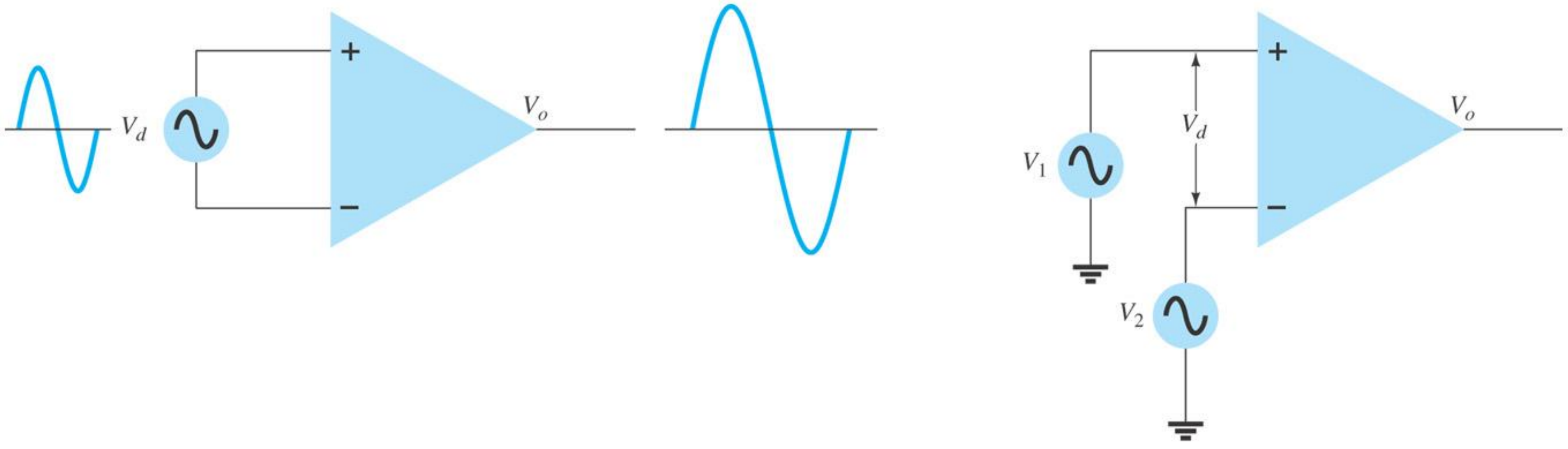
Introduction



Single-ended operation

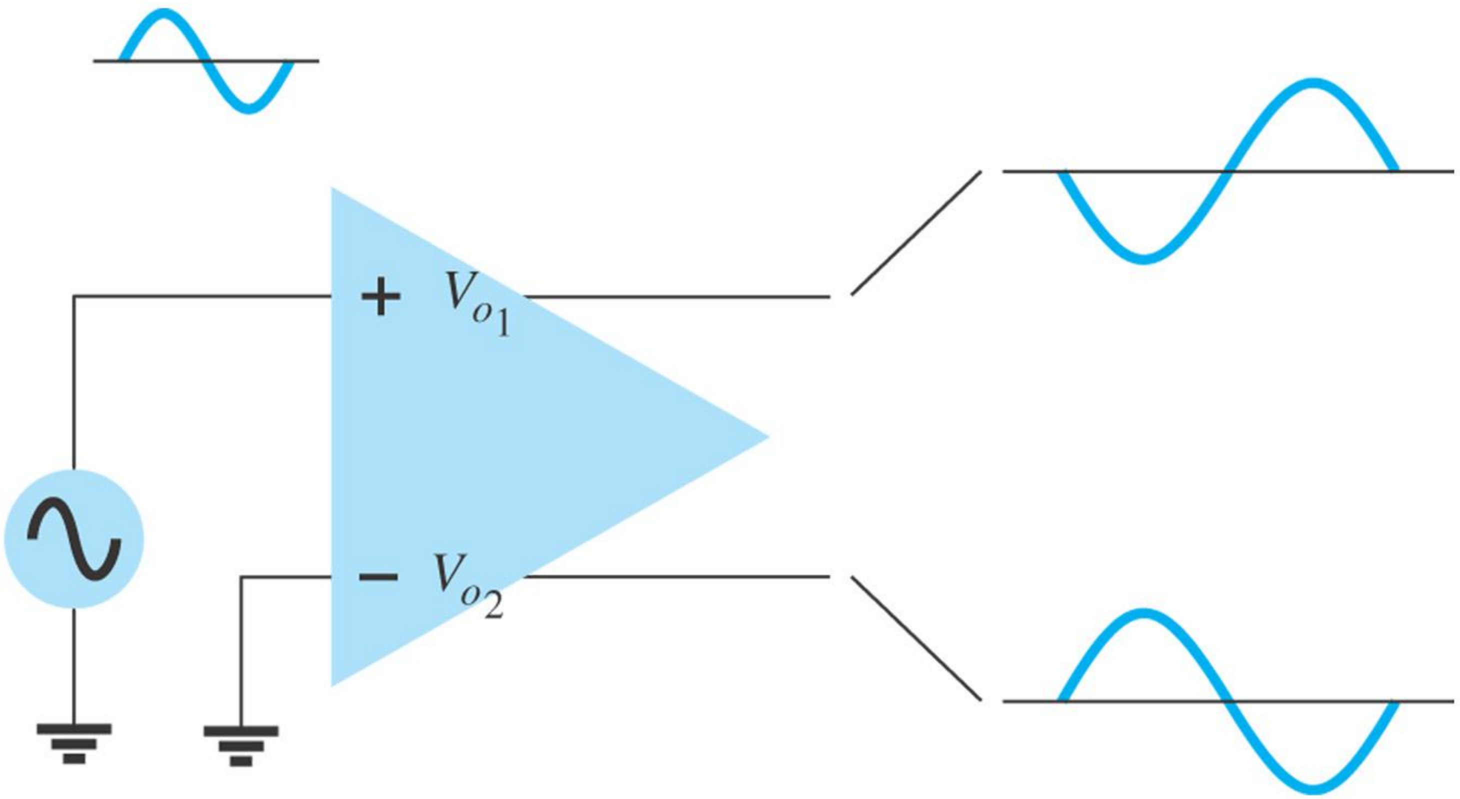
Introduction



(a) (b)

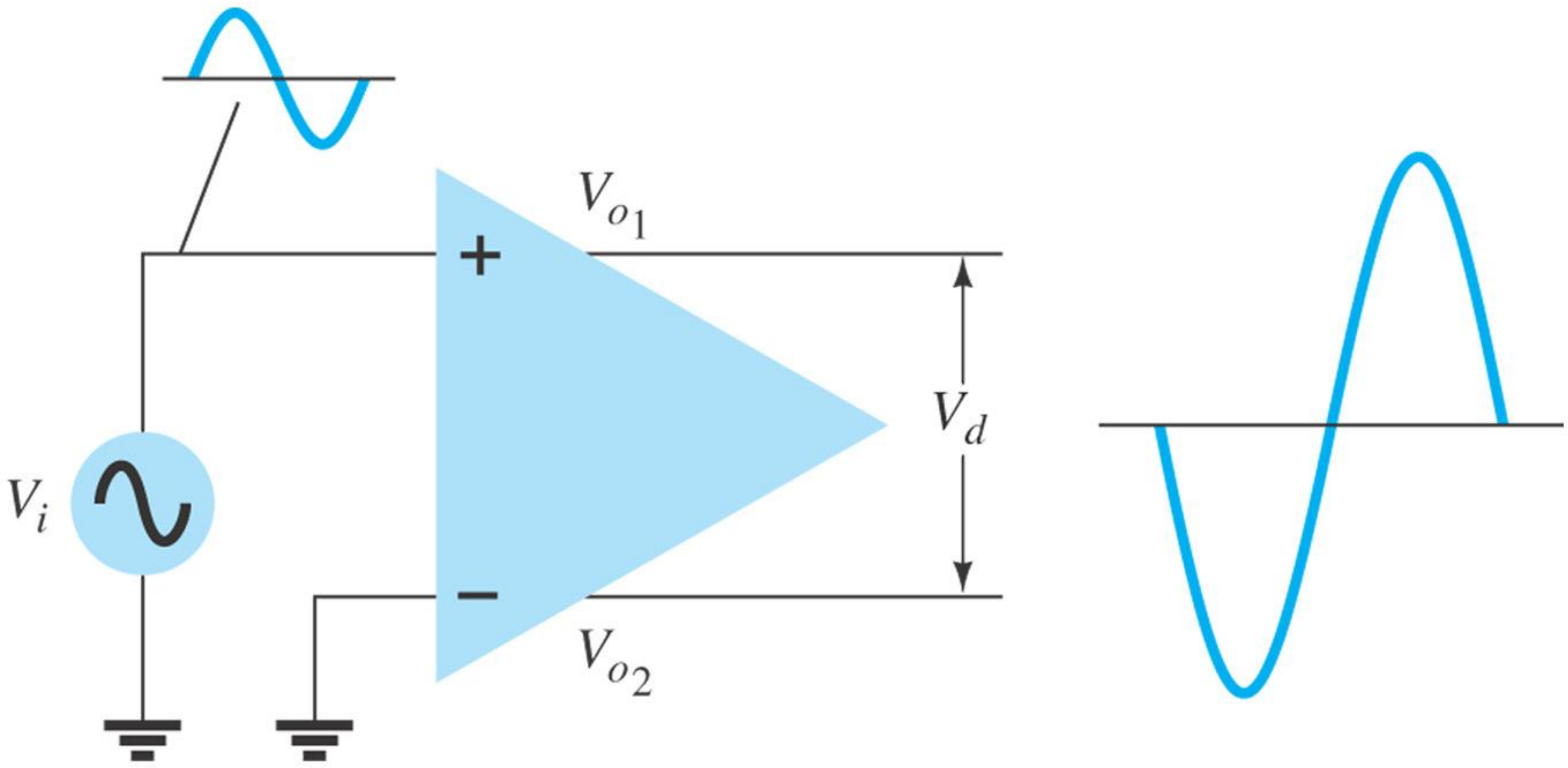
Double-ended (differential) operation.

Introduction



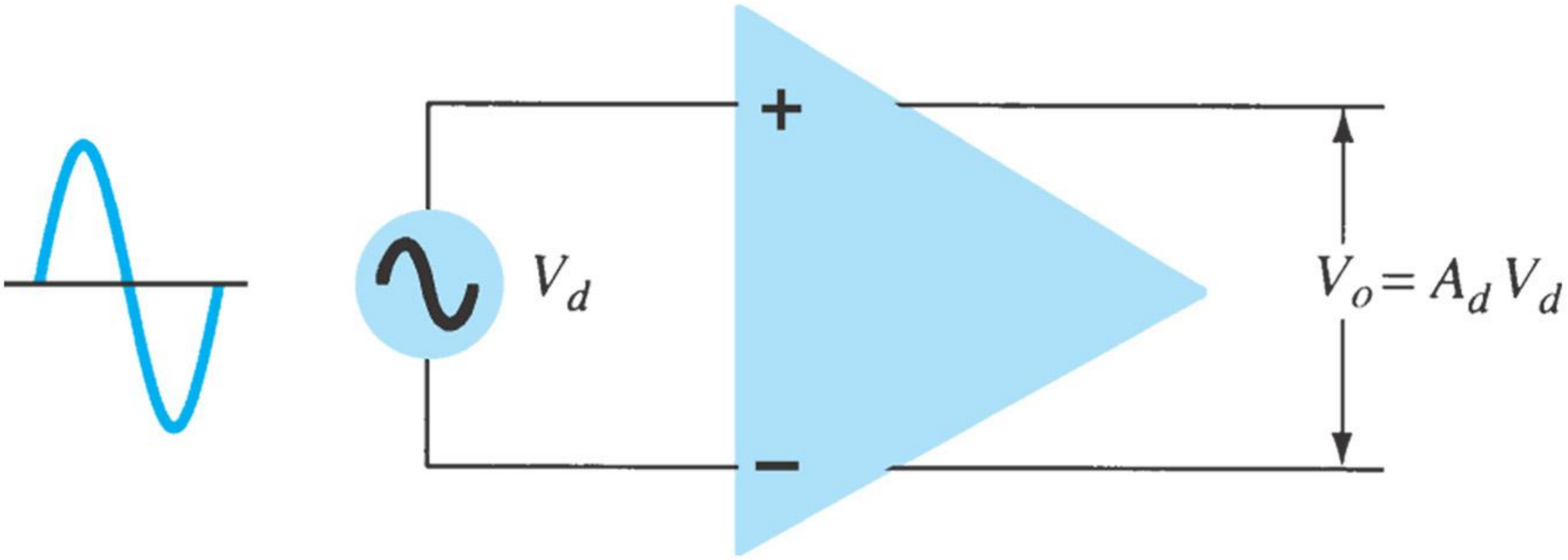
Double-ended output with single-ended input

Introduction



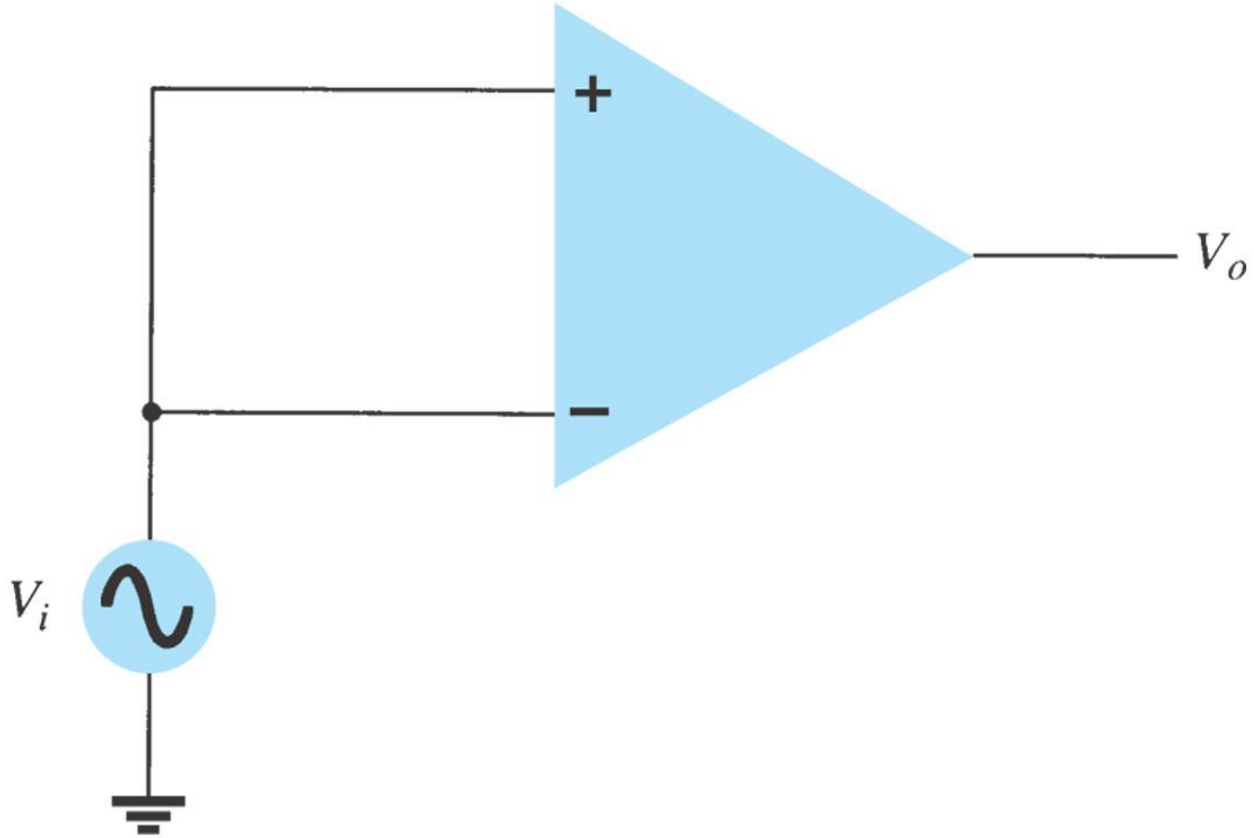
Double-ended output

Introduction



Differential-input, differential-output operation

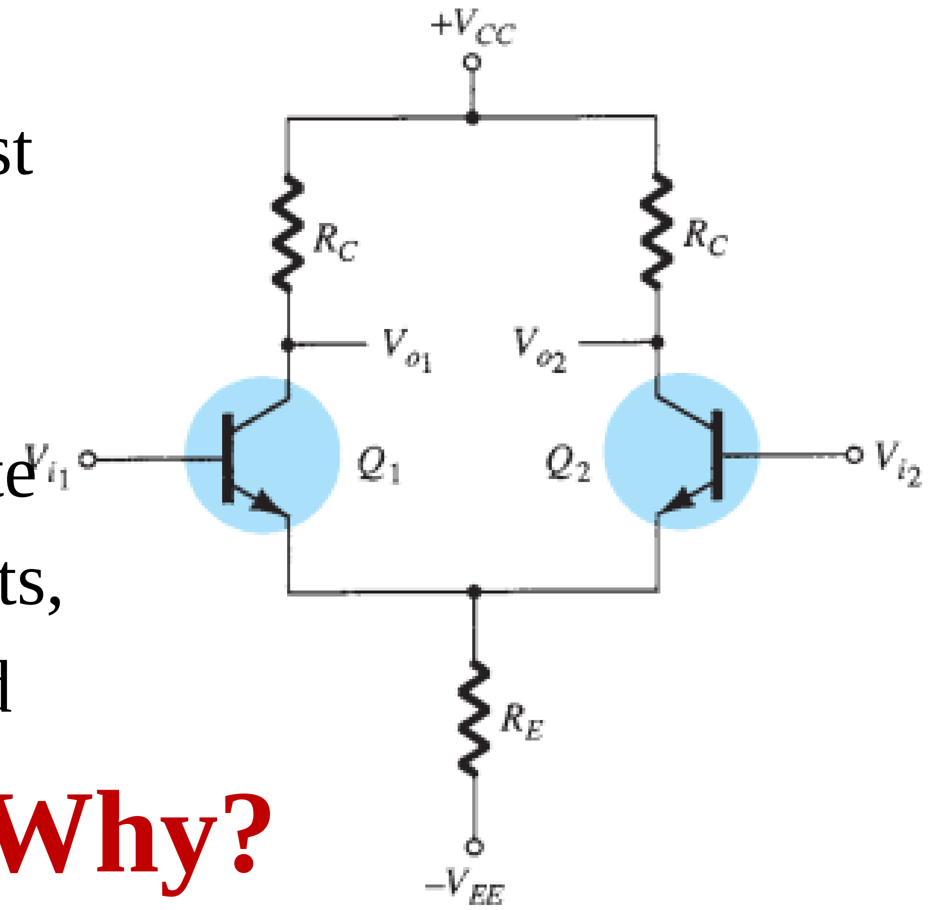
Introduction



Common-mode operation

Differential Amplifier Circuits

- The differential amplifier (pair) configuration is the most widely used building block in analog IC design.
- The circuit has two separate inputs and two separate outputs, and the emitters are connected together.
- Two separate voltage supplies.

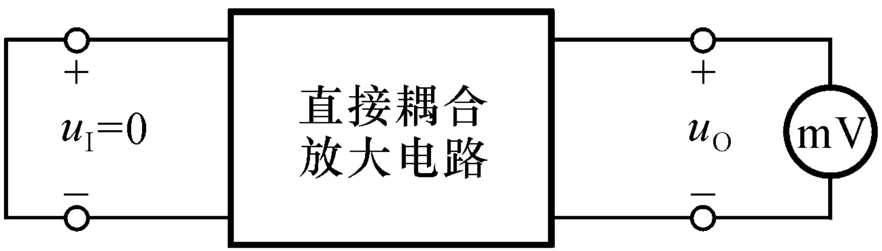


Why?

Basic differential amplifier circuit

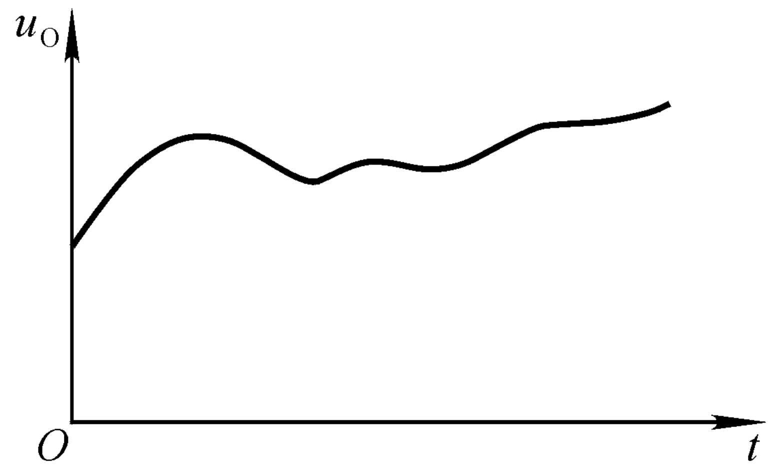
Differential Amplifier Circuits

Reasons:



$$v_i = 0$$
$$v_o \neq 0$$

(a)

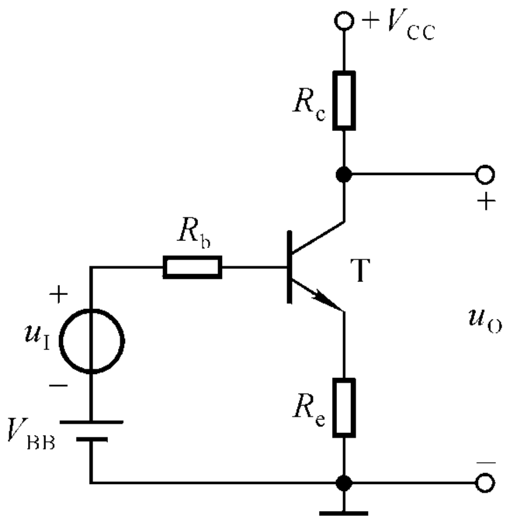


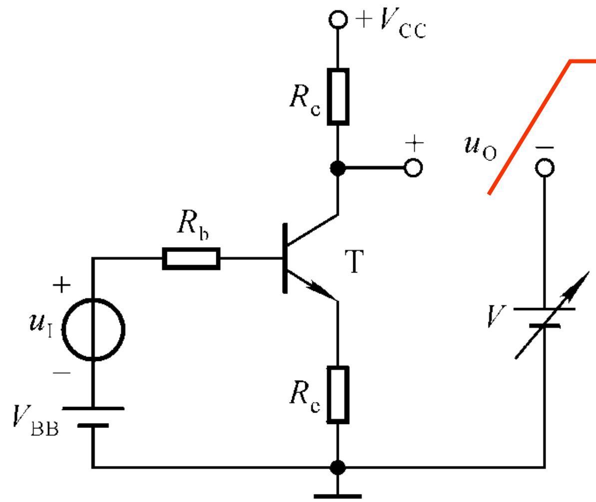
(b)

Direct coupling between signal source and amplifier will easily cause Temperature Drift (Zero Drift).

What shall we do?

Differential Amplifier Circuits



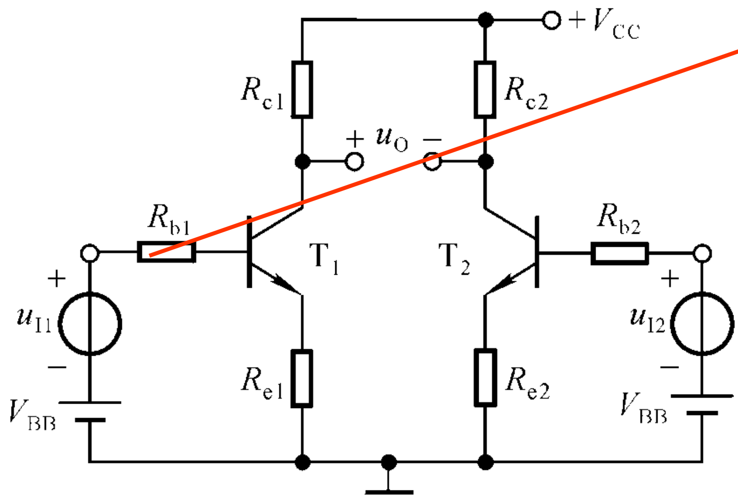


$v_i = 0$

$v_o = 0$

T1 and T2 are idential transistors

$R_{b1} = R_{b2}$, $R_{c1} = R_{c2}$, $R_{e1} = R_{e2}$

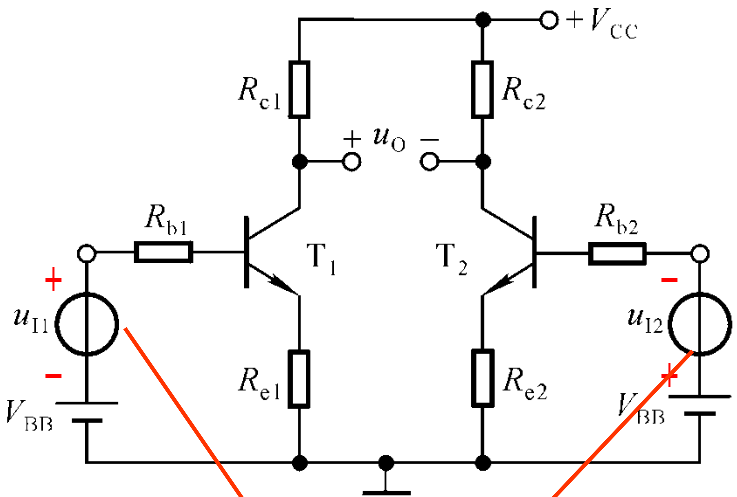


$v_{i1} = v_{i2}$

Common-mode input signal

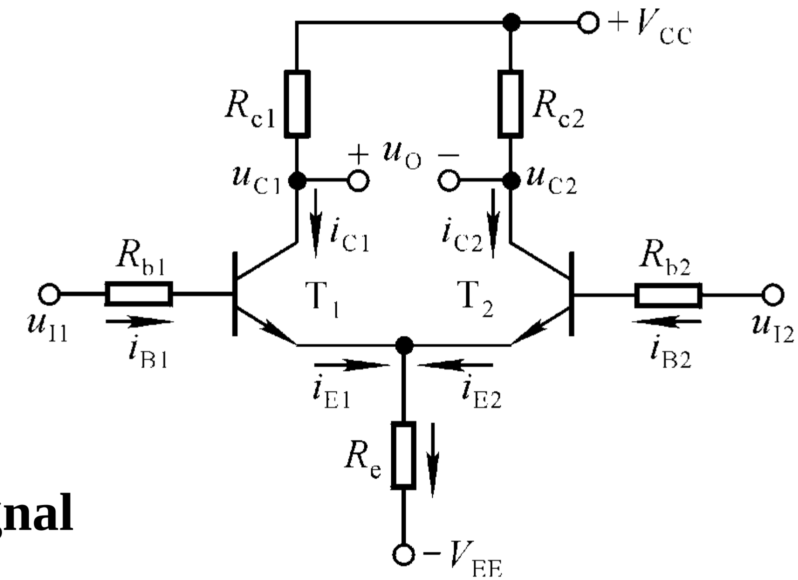
$v_o = 0$

Differential Amplifier Circuits

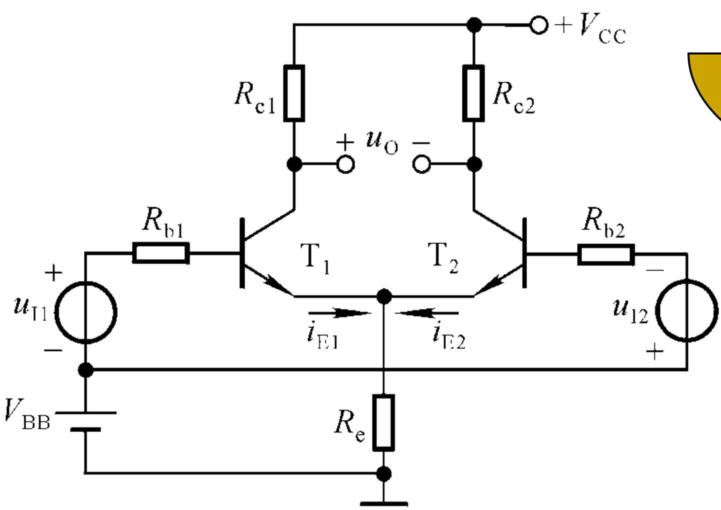


$v_{i1} = -v_{i2}$

Differential input signal



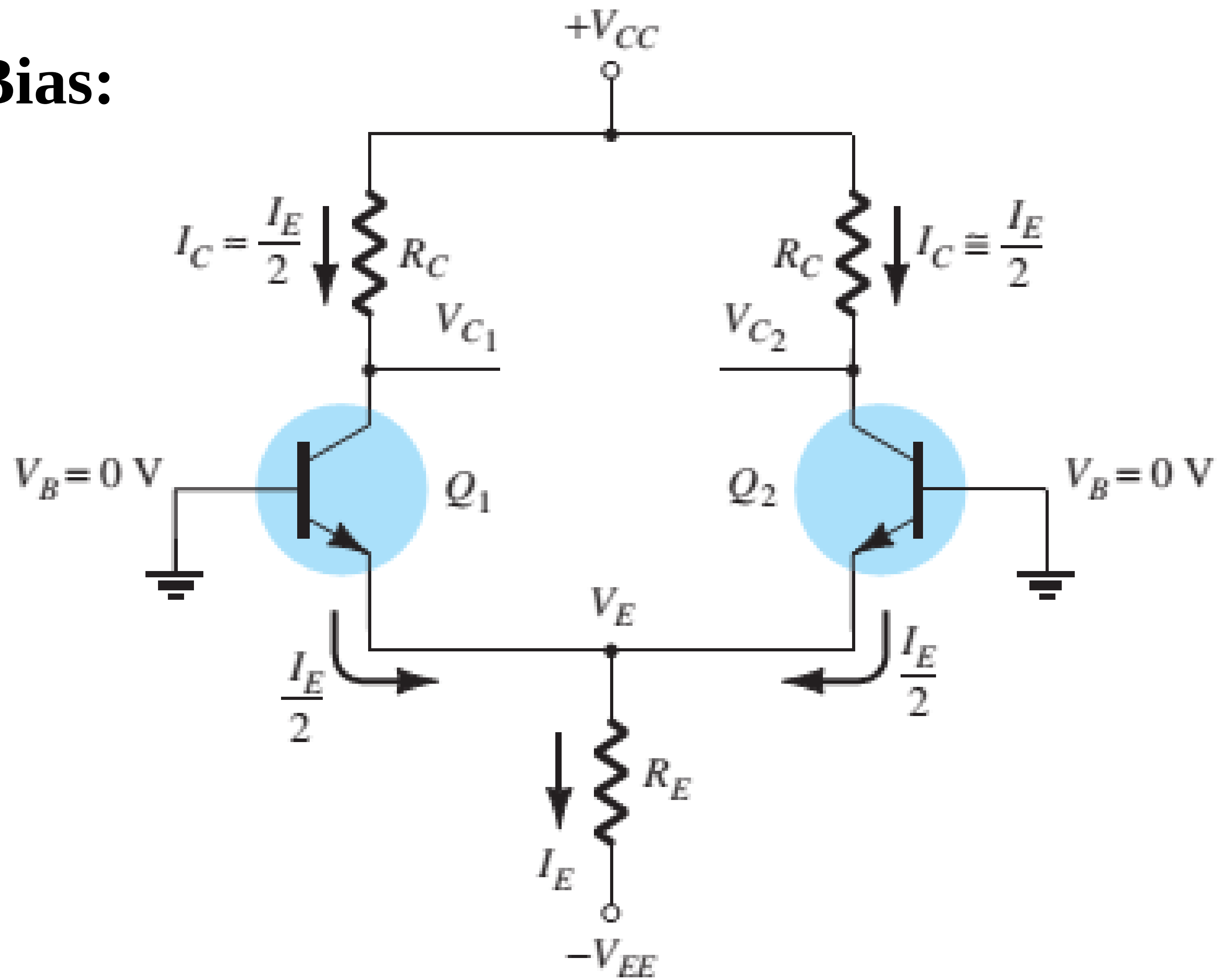
Typical Circuit



- **One goal of the design of differential amplifiers is to minimize the effect fo the common-mode input signal.**

Differential Amplifier Circuits

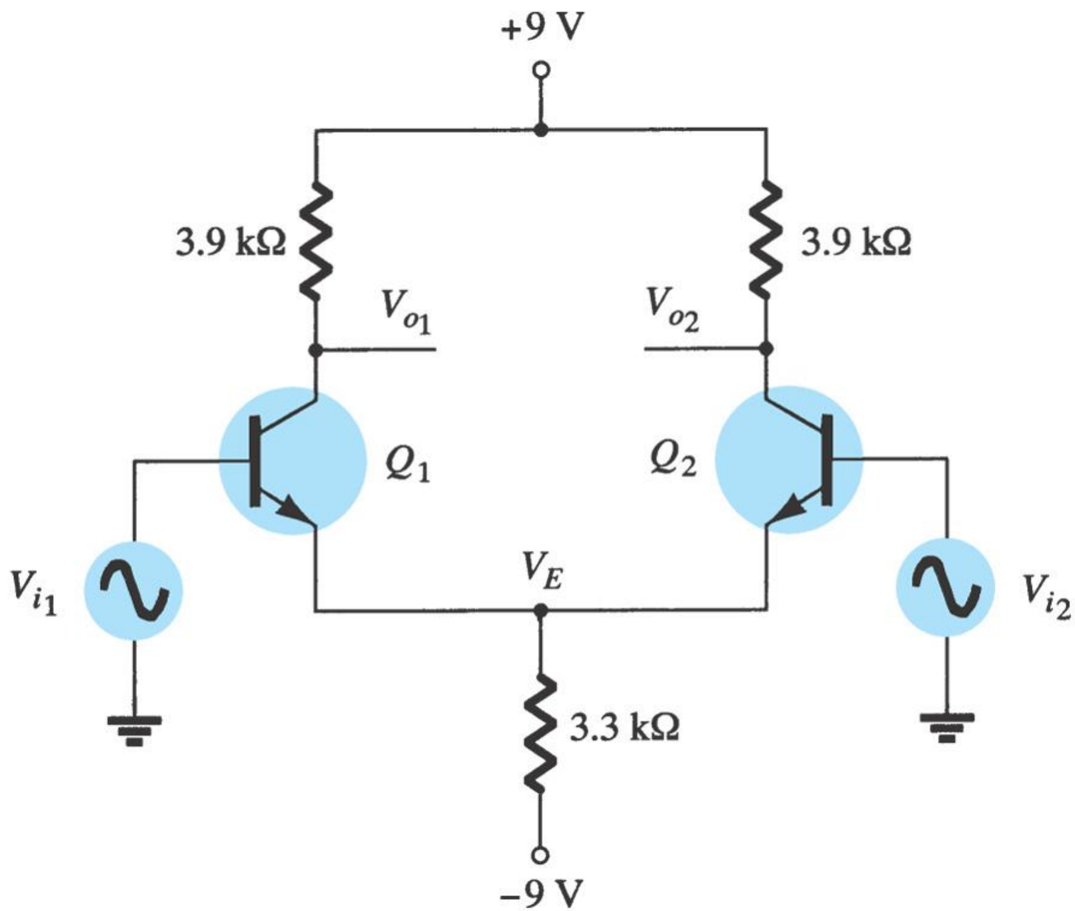
DC Bias:



Differential Amplifier Circuits

Example:

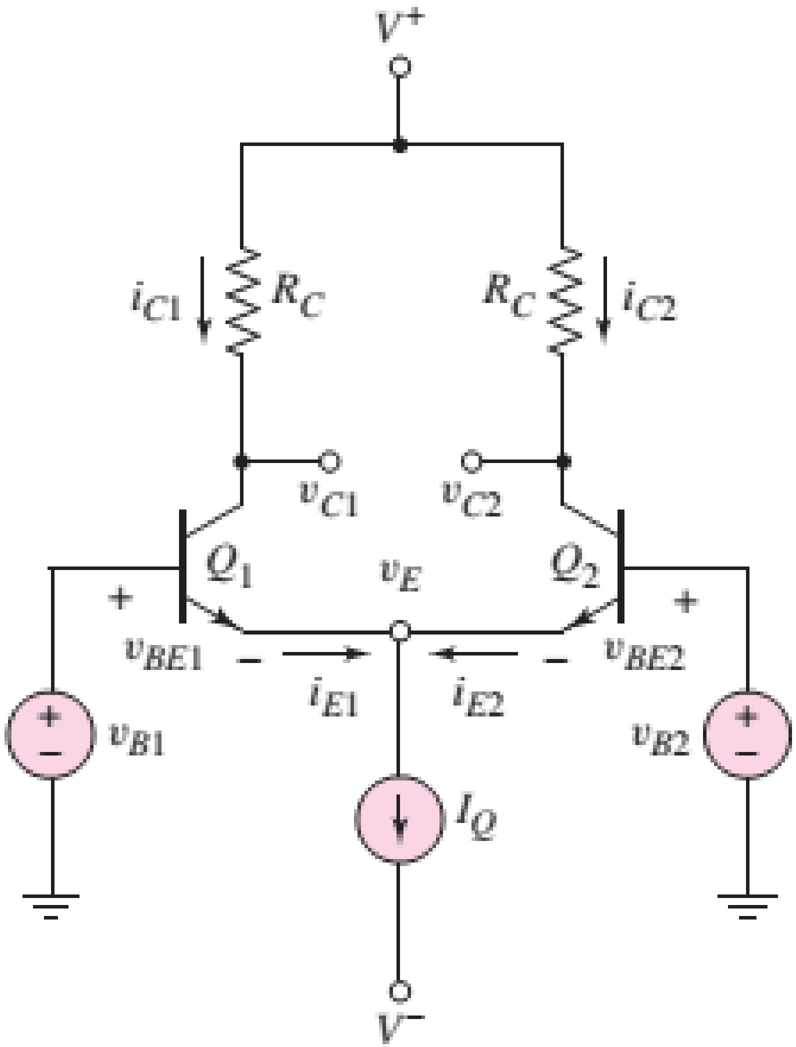
Calculate the dc voltages and currents in the circuit



Differential Amplifier Circuits

Exercise:

For the differential amplifier, the parameters are:$V^+ = 10V, V^- = -10V, I_Q = 1mA, R_C = 10k\Omega, \beta = 200$.Find the voltages$V_E, V_{C1}, V_{C2}$,for $v_{B1} = v_{B2} = 0$.



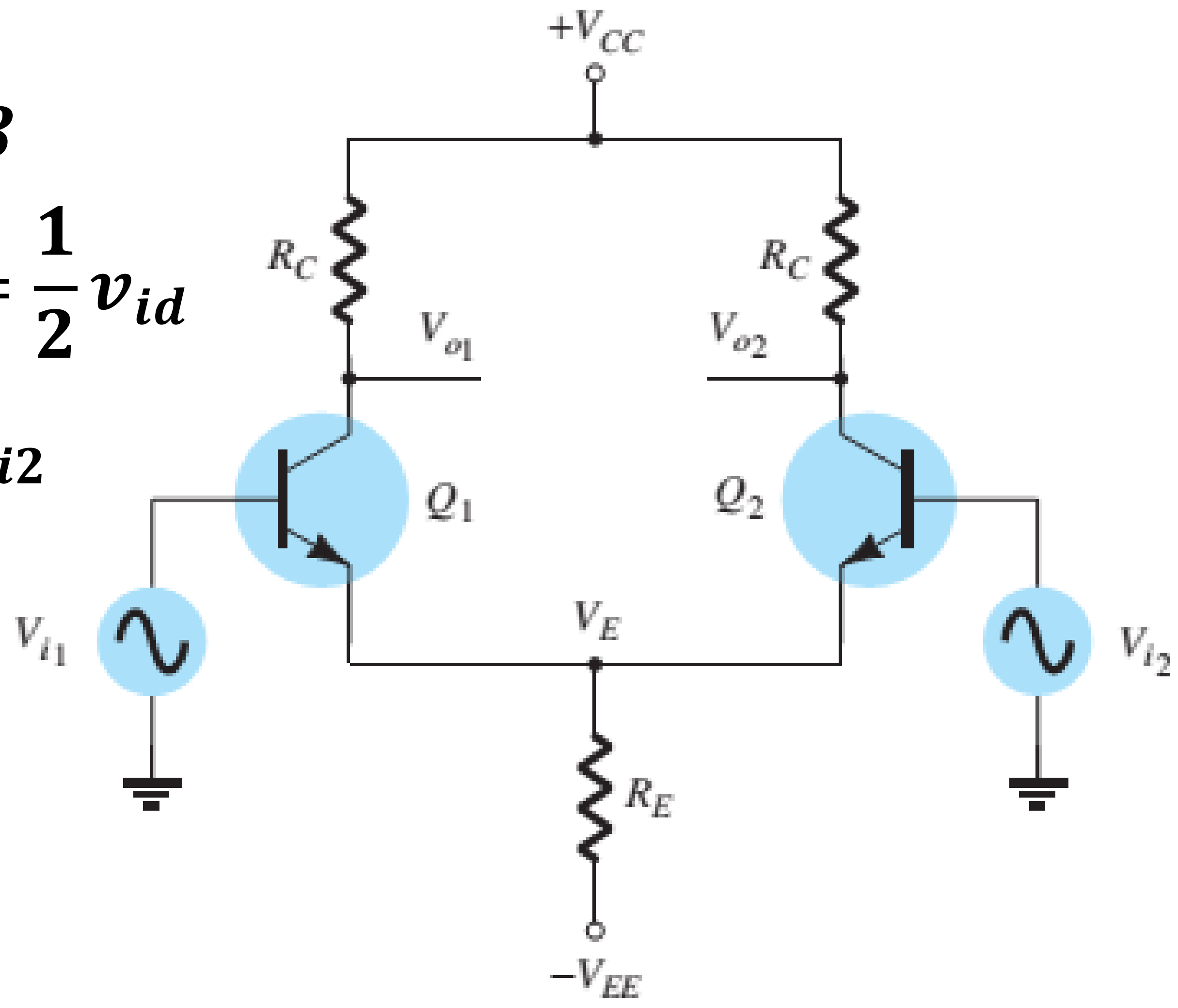
AC Operation of Diff-Amp

Double-Ended AC Voltage Gain

$$\beta_1 = \beta_2 = \beta$$

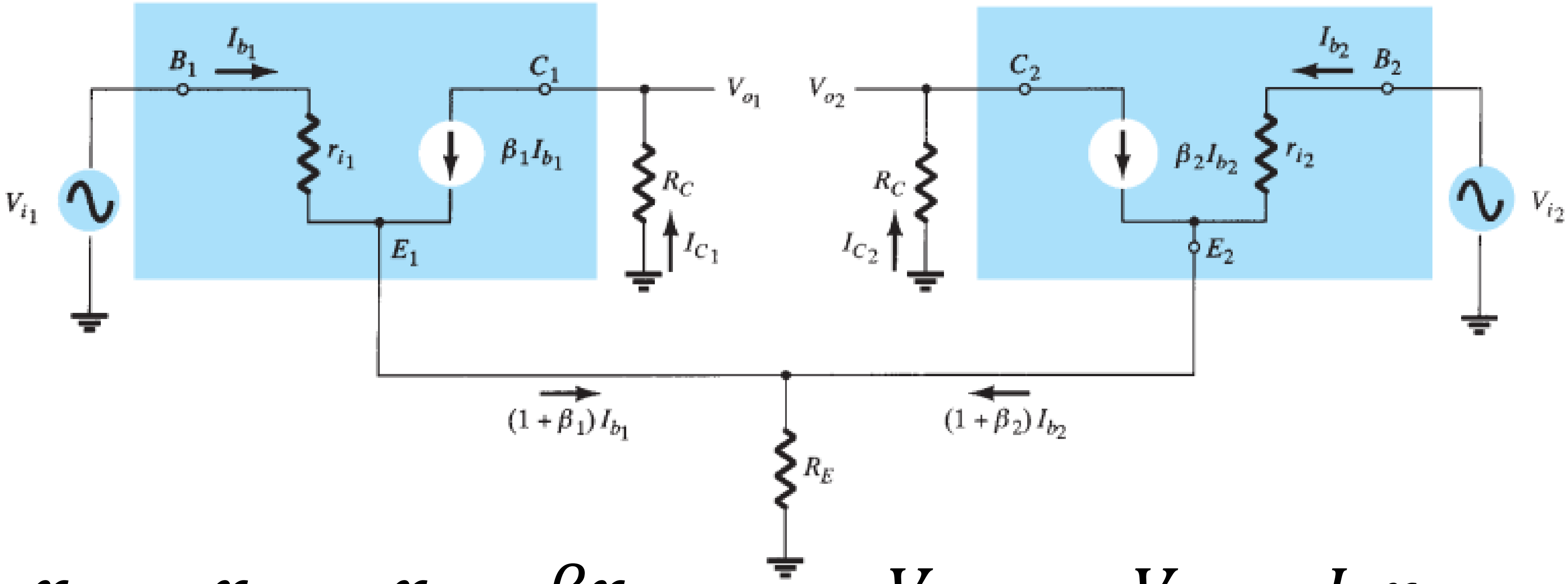
$$v_{i1} = -v_{i2} = \frac{1}{2} v_{id}$$

$$v_{id} = v_{i1} - v_{i2}$$



AC Operation of Diff-Amp

Double-Ended AC Voltage Gain



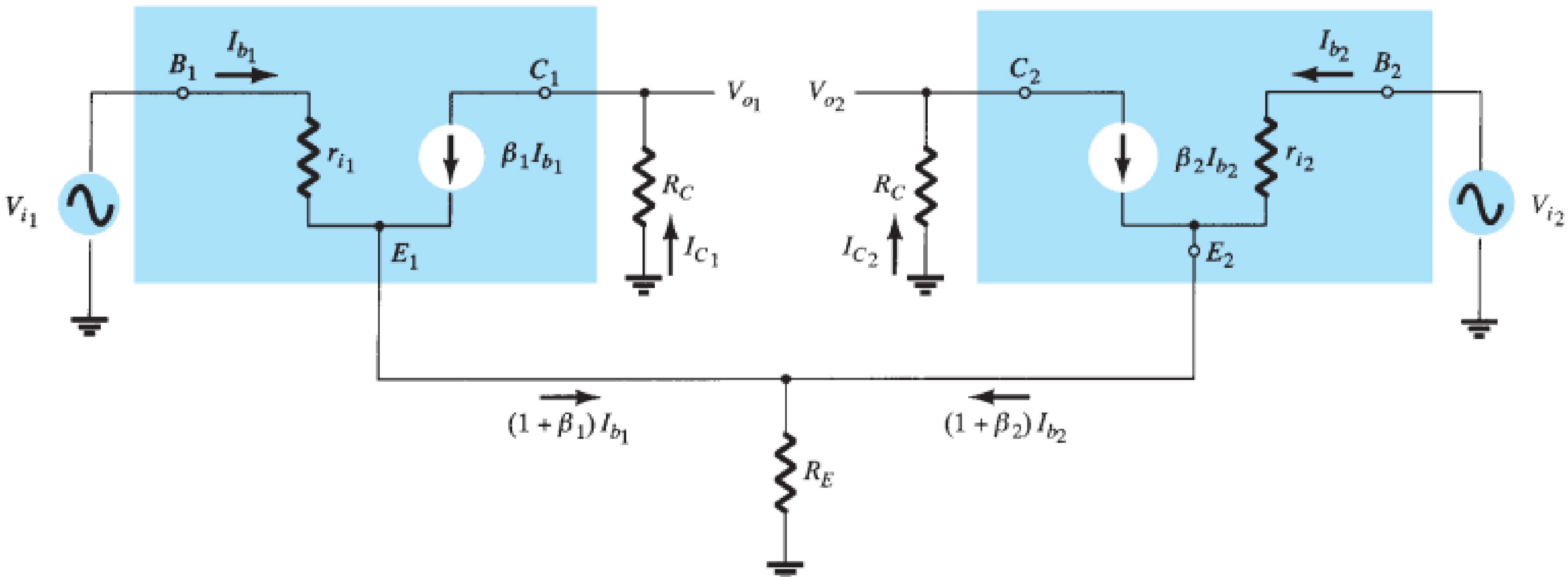
$$r_{i1} = r_{i2} = r_i = \beta r_e$$

$$V_{i1} = -V_{i2} = I_b r_i$$

$$I_{b1} = -I_{b2} = I_b$$

$$V_{id} = 2 I_b r_i = 2\beta I_b r_e$$

AC Operation of Diff-Amp



$$V_{o1} = -I_{c1}R_C = -\beta I_b R_C$$

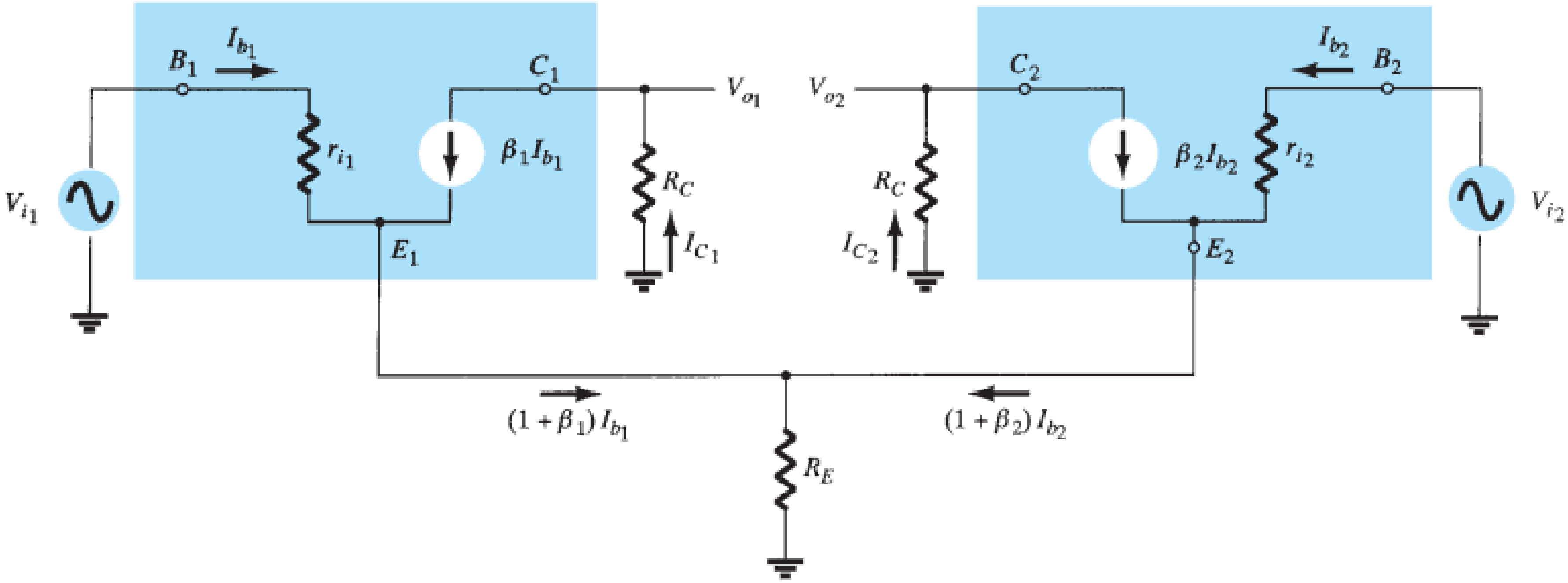
$$V_{o2} = -I_{c2}R_C = \beta I_b R_C$$

$$V_o = V_{o1} - V_{o2} = -2\beta I_b R_C$$

$$A_{vd} = \frac{V_o}{V_{id}} = \frac{-2\beta I_b R_C}{2\beta I_b r_e}$$

$$= -\frac{R_C}{r_e}$$

AC Operation of Diff-Amp



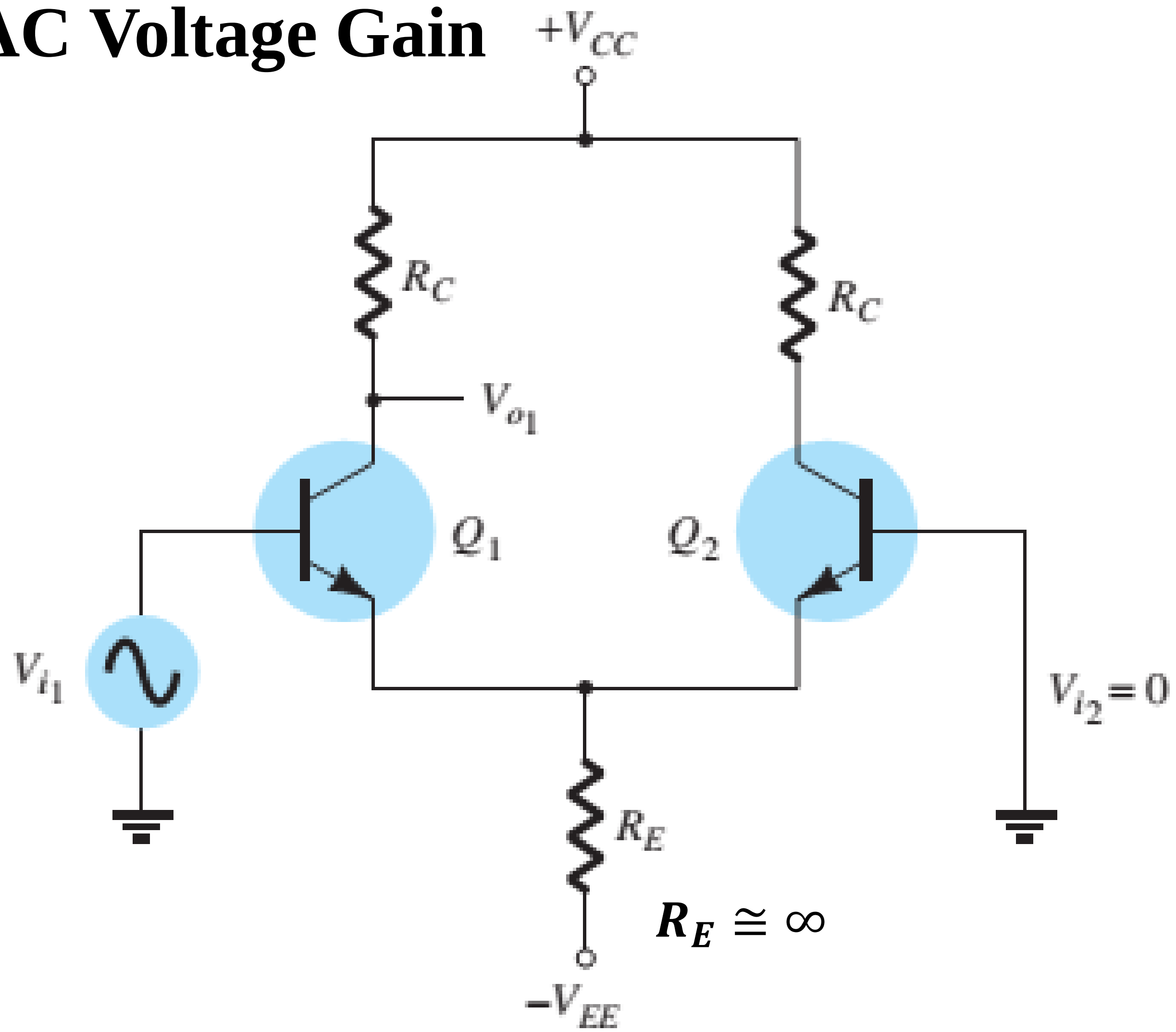
If the output signal is from collector 1 or collector 2 ?

$$A_{v1} = \frac{V_{o1}}{V_{id}} = \frac{-\beta I_b R_C}{2\beta I_b r_e} = -\frac{R_C}{2r_e}$$

$$A_{v2} = \frac{V_{o2}}{V_{id}} = \frac{\beta I_b R_C}{2\beta I_b r_e} = \frac{R_C}{2r_e}$$

AC Operation of Diff-Amp

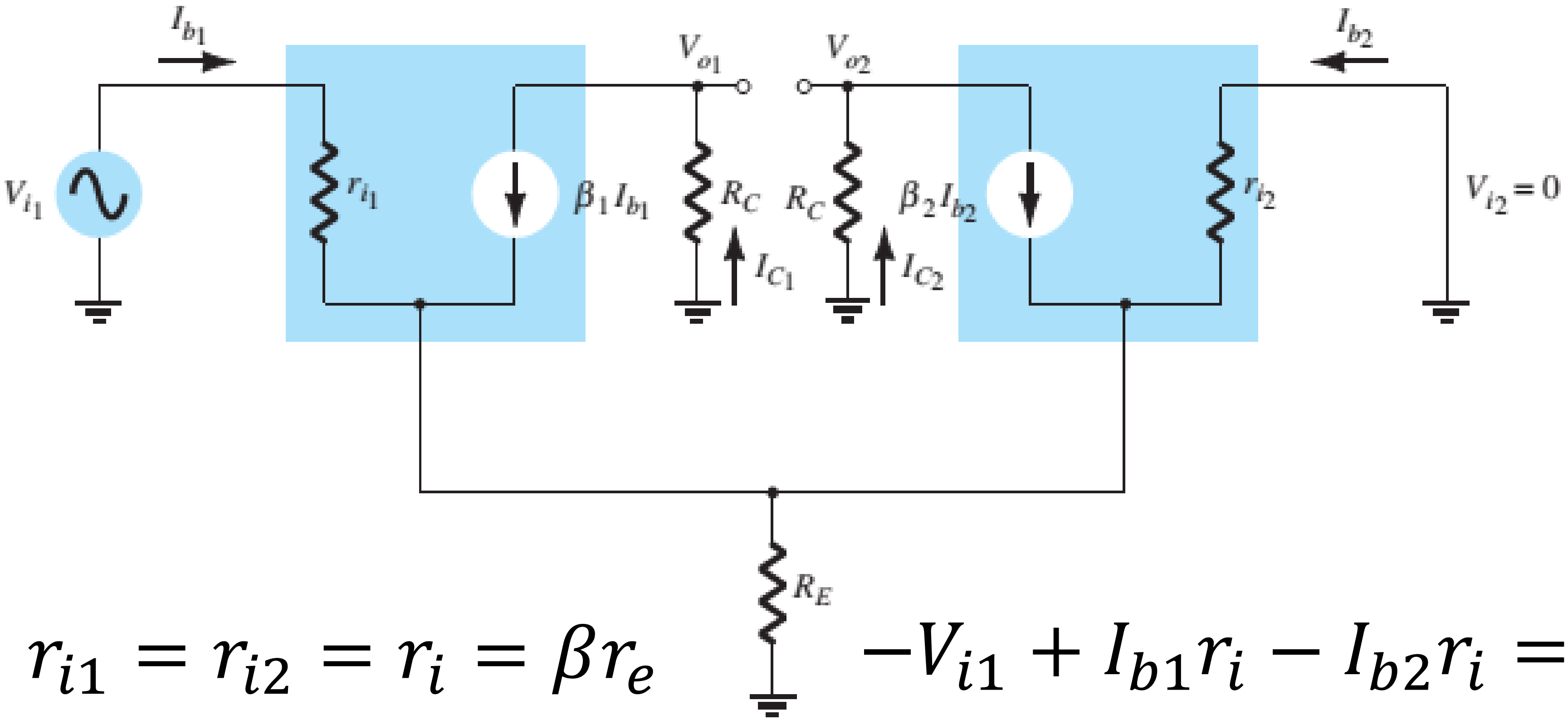
Single-Ended AC Voltage Gain



$R_E \cong \infty$

AC Operation of Diff-Amp

Single-Ended AC Voltage Gain



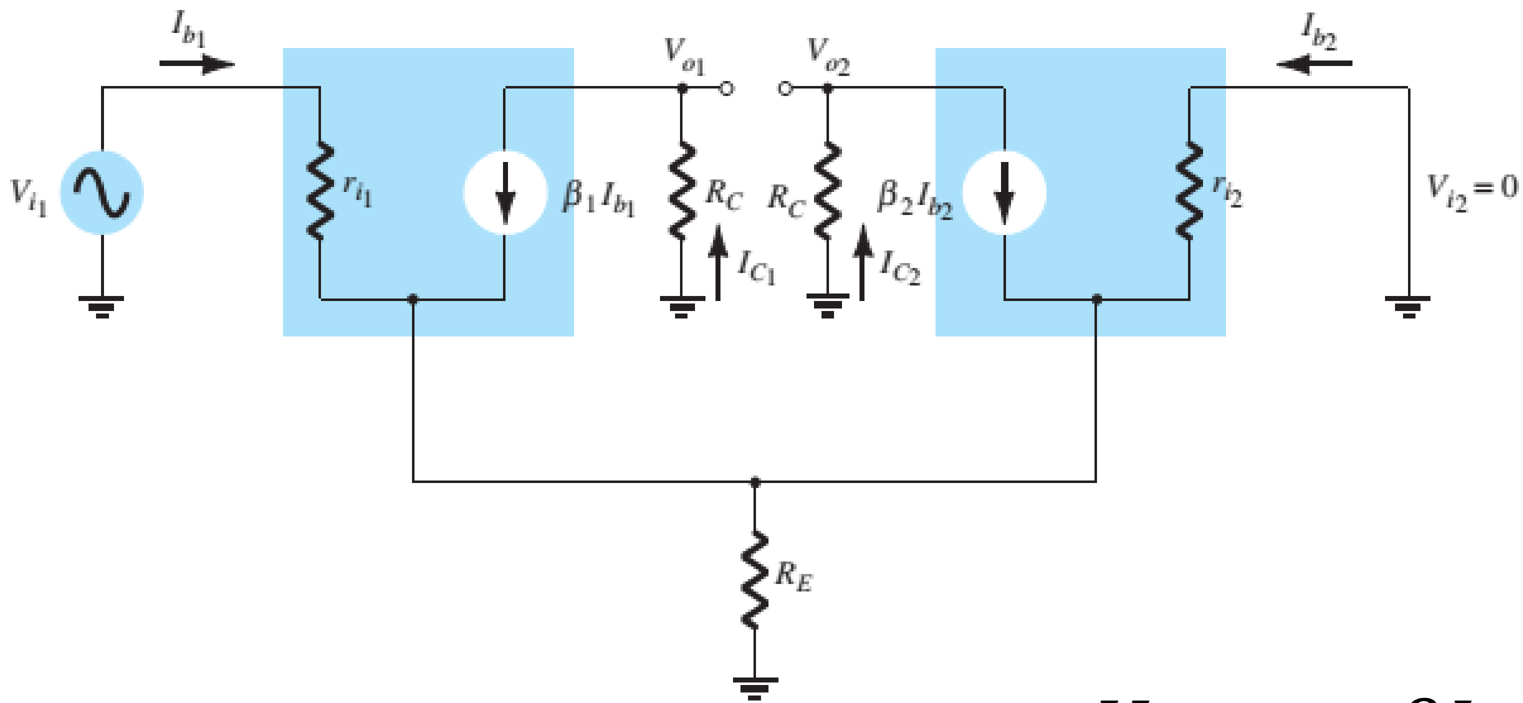
$$r_{i1} = r_{i2} = r_i = \beta r_e$$

$$I_{b1} = -I_{b2} = I_b$$

$$-V_{i1} + I_{b1} r_i - I_{b2} r_i = 0$$

$$V_{i1} - I_b r_i - I_b r_i = 0$$

AC Operation of Diff-Amp



$$V_i = 2I_b r_i = 2\beta I_b r_e$$

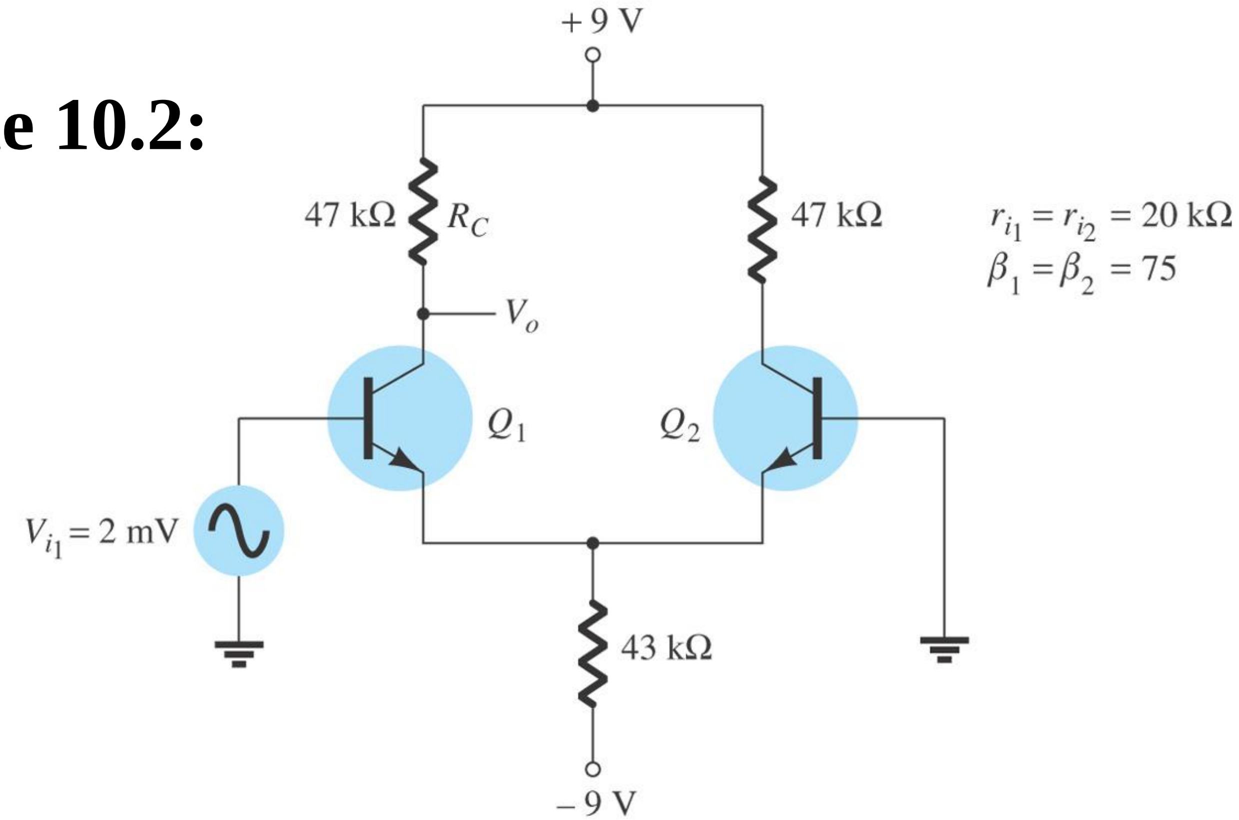
$$V_{o1} = -I_{c1}R_C = -\beta I_b R_C$$

$$A_v = \frac{V_{o1}}{V_{i1}} = \frac{-\beta I_b R_C}{2\beta I_b r_e}$$

$$= -\frac{R_C}{2r_e}$$

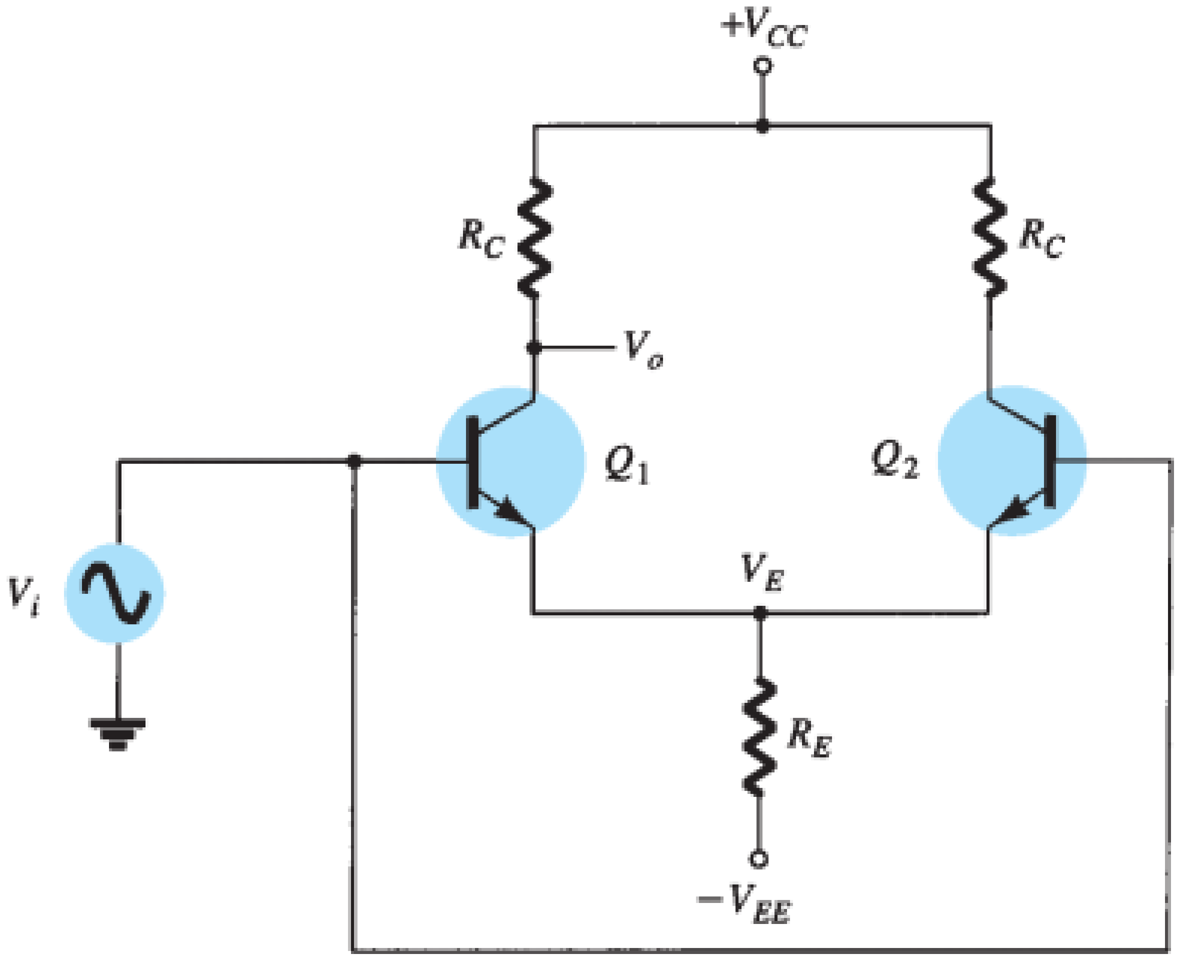
AC Operation of Diff-Amp

Example 10.2:

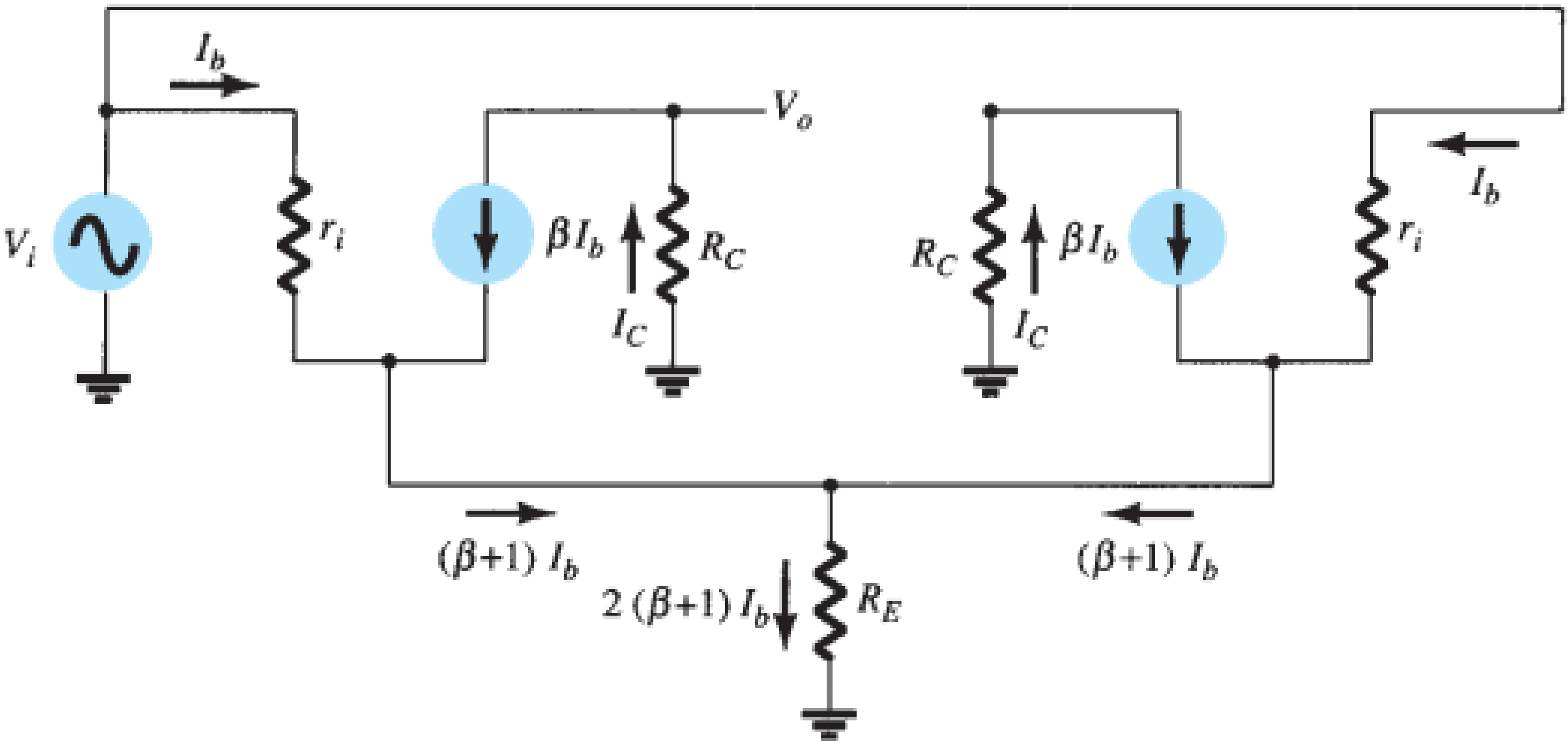


Circuit for Examples 10.2 and 10.3

Common-Mode Operation of Diff-Amp



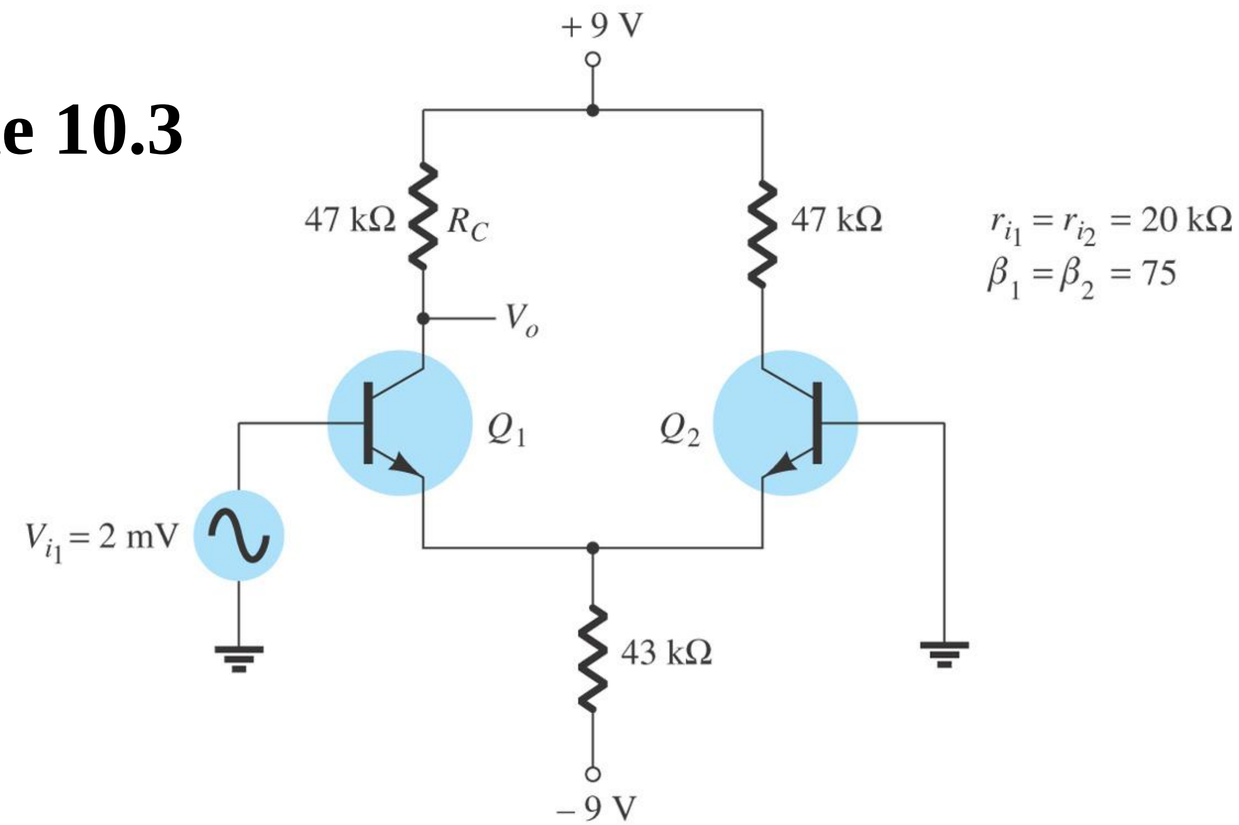
Common-Mode Operation of Diff-Amp



$$A_v = \frac{V_o}{V_i} = \frac{-\beta R_C}{\beta r_e + 2(1+\beta)R_E}$$

Common-Mode Operation of Diff-Amp

Example 10.3



Circuit for Examples 10.2 and 10.3

AC Operation of Diff-Amp

Differential-mode input voltage:

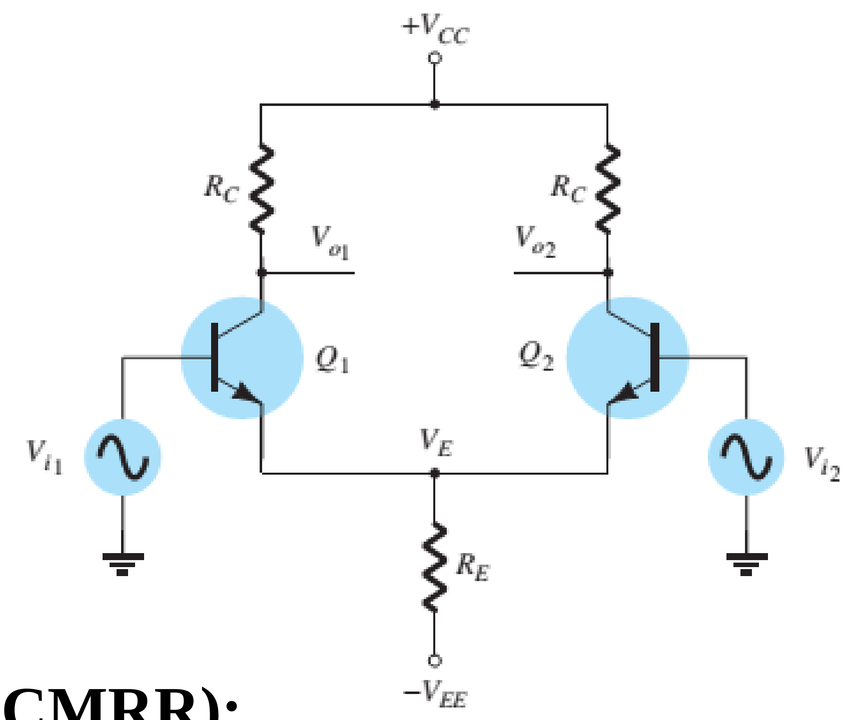
$$V_d = V_{i1} - V_{i2}$$

Common-mode input voltage:

$$V_c = \frac{1}{2}(V_{i1} + V_{i2})$$

Output Voltage:

$$V_o = A_d V_d + A_c V_c$$



Common-mode Rejection Ratio (CMRR):

$$CMRR = \left|\frac{A_d}{A_c}\right| \qquad CMRR(log) = 20log_{10}\left|\frac{A_d}{A_c}\right|$$

AC Operation of Diff-Amp

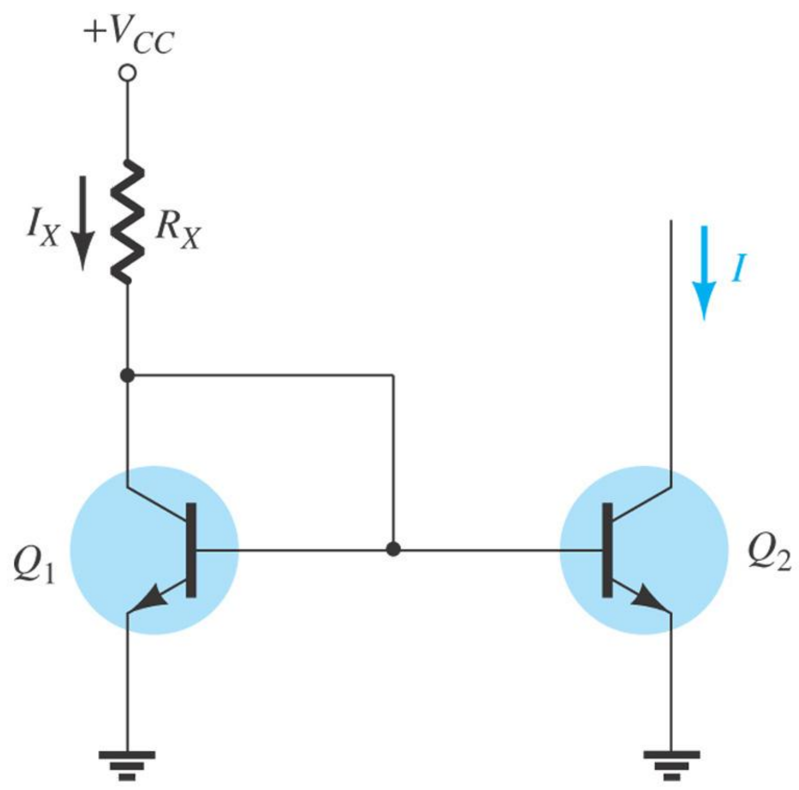
Example

1. Find the differential and common-mode components of the input signal applied to a diff-amp for input voltages of (a) $v_{i1} = 2.1V, v_{i2} = 2.12V$; $(b) v_{i1} = 0.25 - 0.002 sin\omega t\ V, v_{i2} = 0.5 + 0.002 sin\omega t\ V.$

2. Assume the differential-mode gain of a diff-amp is $A_d = 80$,and the common-mode gain is $A_{cm} = -0.2$. Determine the output voltage for input signals of:
(a) $v1 = 0.995 \sin \omega t$ V and $v2 = 1.005 \sin \omega t$ V; and (b) $v1 = 2 - 0.005 \sin \omega t$ V and $v2 = 2 + 0.005 \sin \omega t$ V.

Current Mirror Circuits

- **A current mirror circuit provides a constant currrent and is used primarily in integrated circuits.**
- **The constant current is obtained from an output current, which is the reflection or mirror of a constant current developed on one side of the circuit.**
- **The current I_X set by transistor Q_1 and resistor R_X is mirrored in the current I through transistorQ_2.**



Current Mirror Circuits

$$I_B = \frac{I_E}{1+\beta} \approx \frac{I_E}{\beta}$$

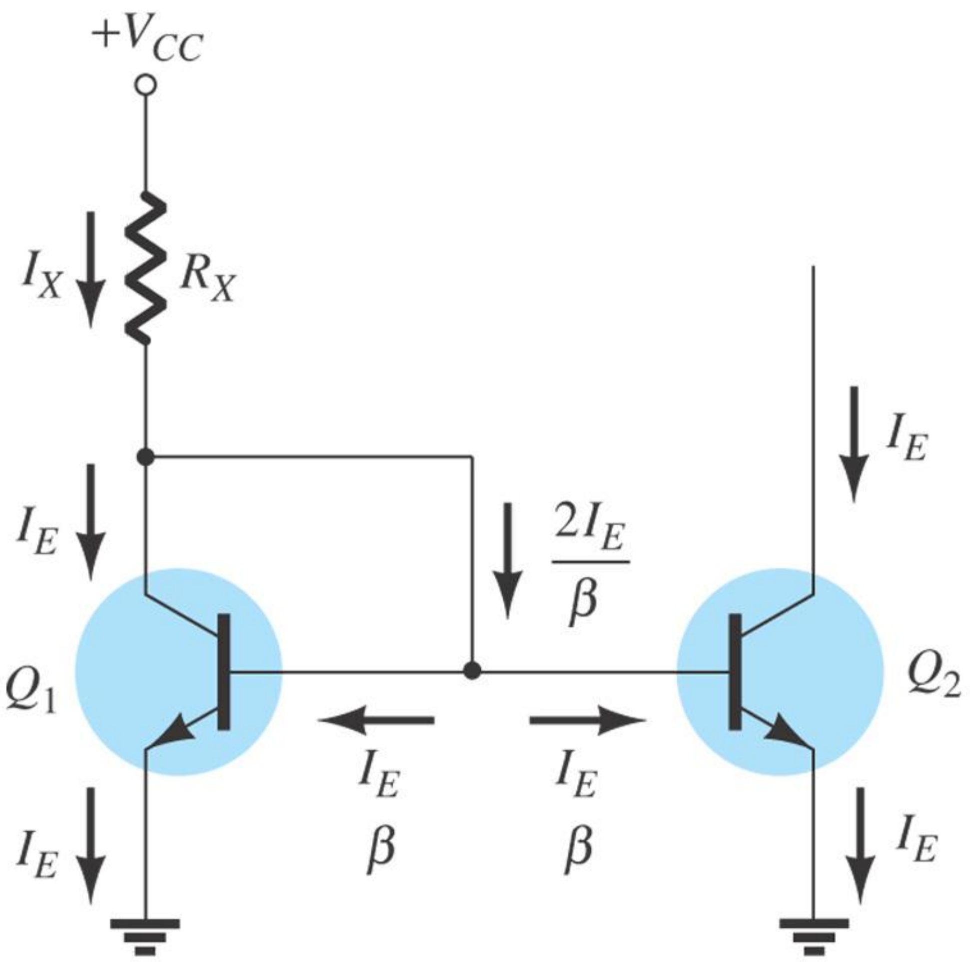
$$I_C \cong I_E$$

$$I_X = I_E + \frac{2I_E}{\beta}$$

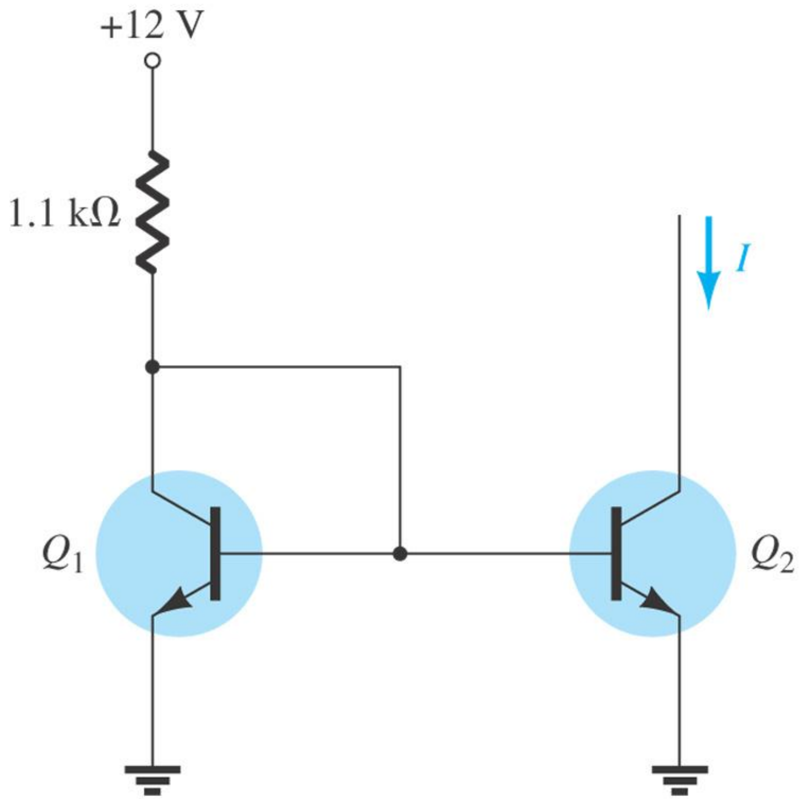
$$= \frac{\beta I_E}{\beta} + \frac{2I_E}{\beta}$$

$$= \frac{\beta+2}{\beta} I_E \approx I_E$$

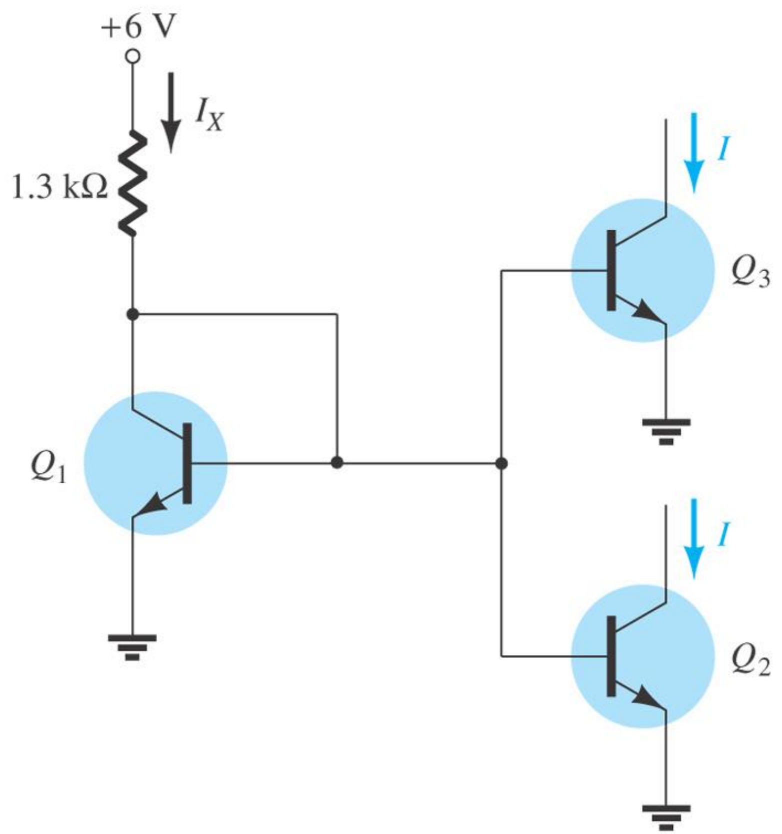
$$I_X = \frac{V_{CC} - V_{BE}}{R_X}$$



Current Mirror Circuits

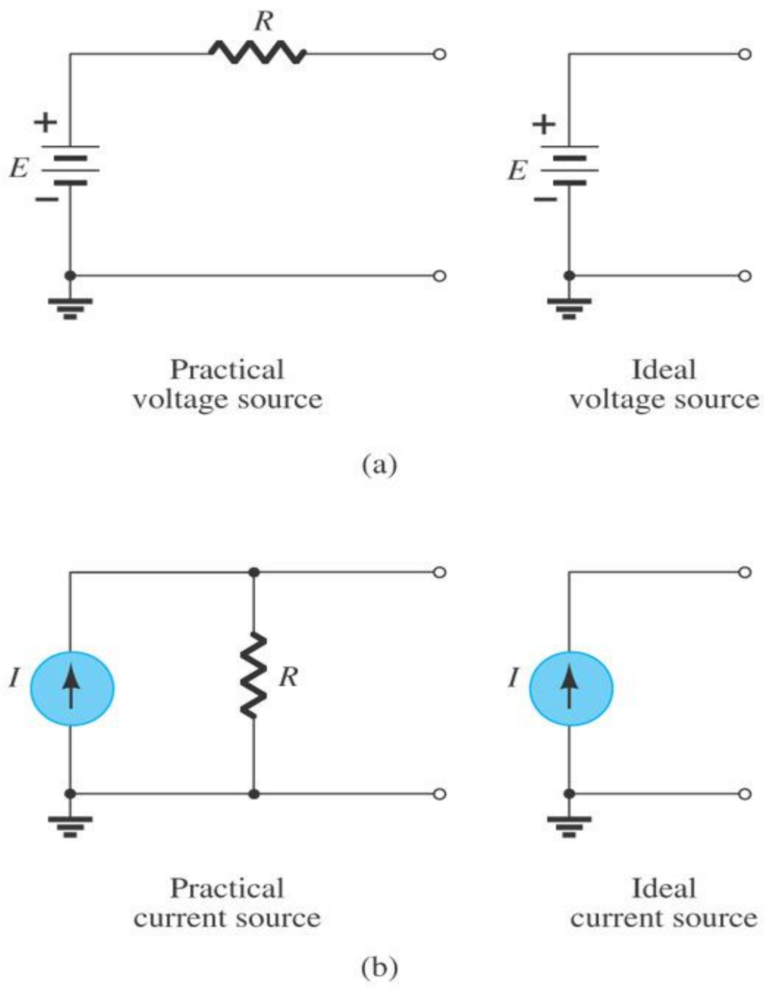


Current mirror circuit for Example 5.27



Current mirror circuit for Example 5.28

Circuit Source Circuits



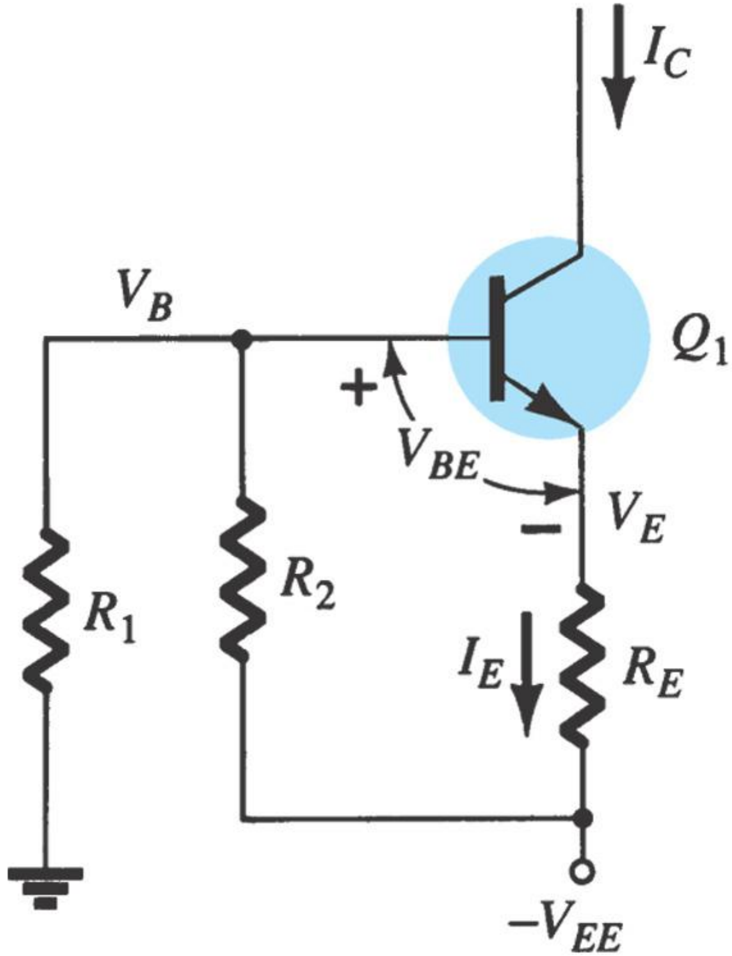
Circuit Source Circuits

$$V_B = \frac{R_1}{R_1 + R_2}(-V_{EE})$$

$$V_E = V_B - 0.7V$$

$$I_E = \frac{V_E - (-V_{EE})}{R_E} \approx I_C$$

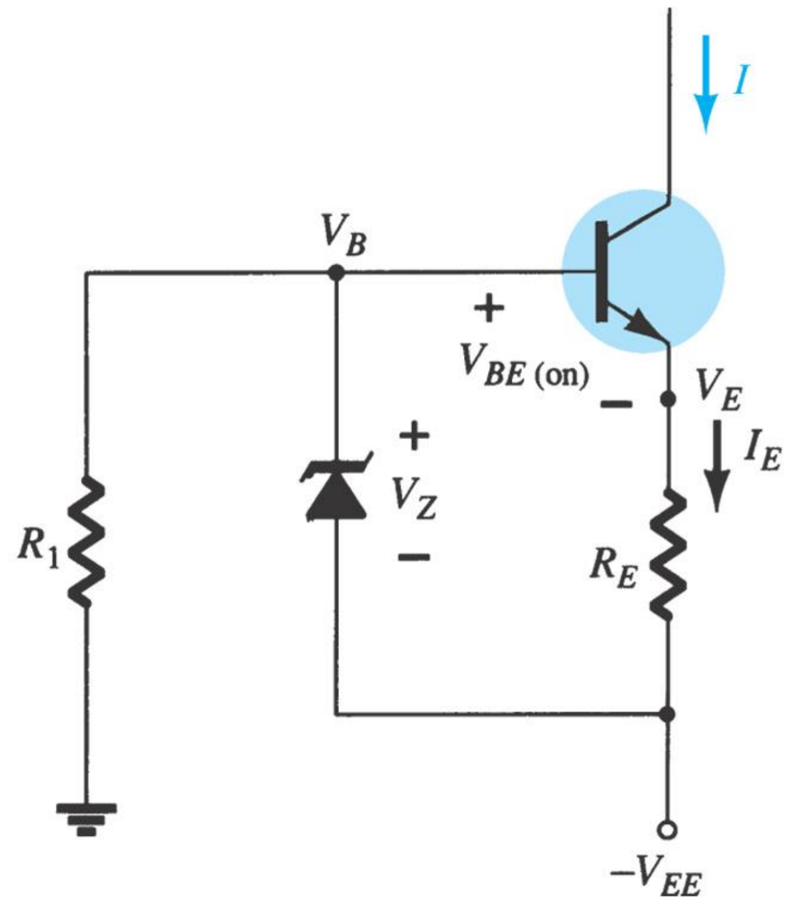
I_C Is the constant current provided by the circuit



Discrete constant-current source

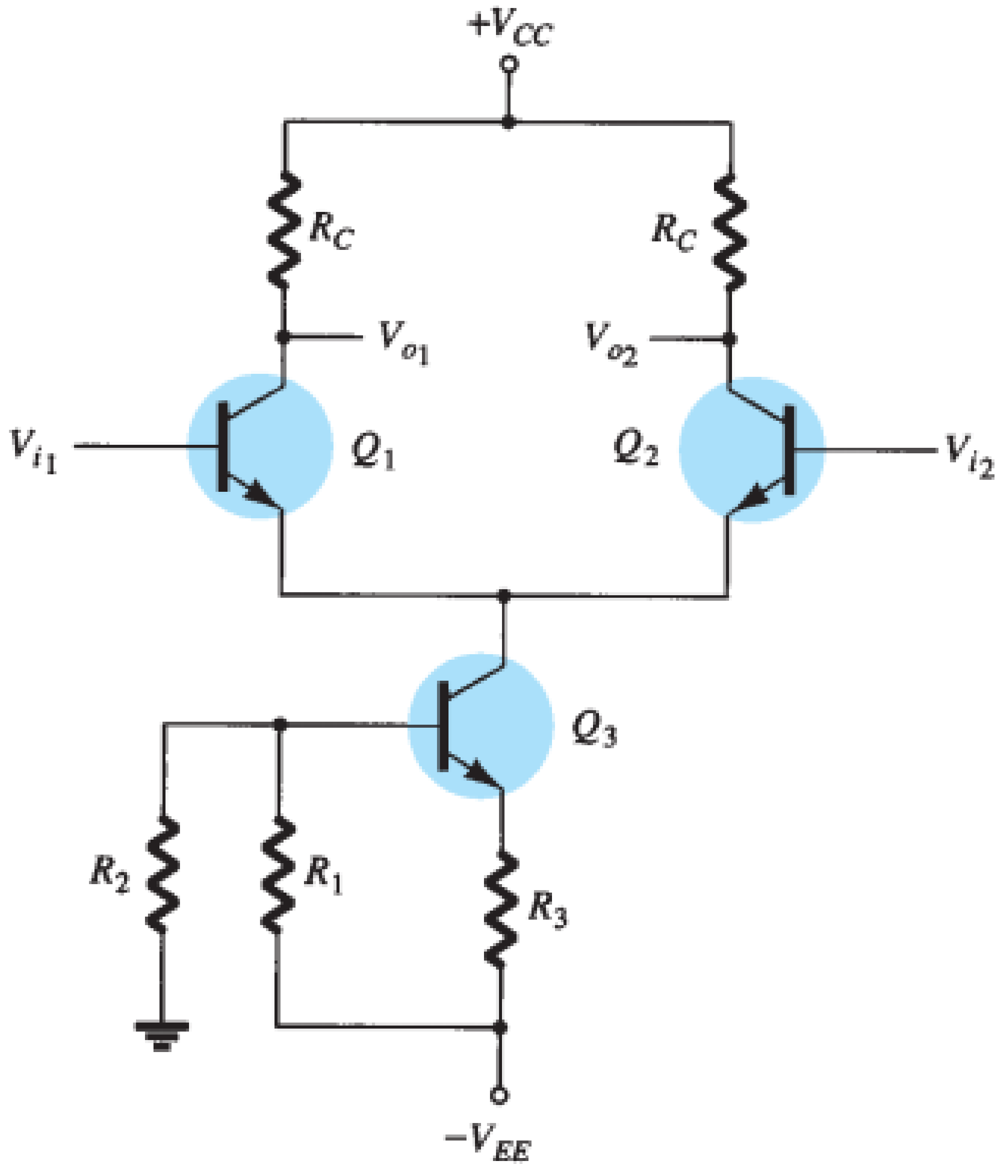
Circuit Source Circuits

$$I \approx I_E = \frac{V_Z - V_{BE}}{R_E}$$

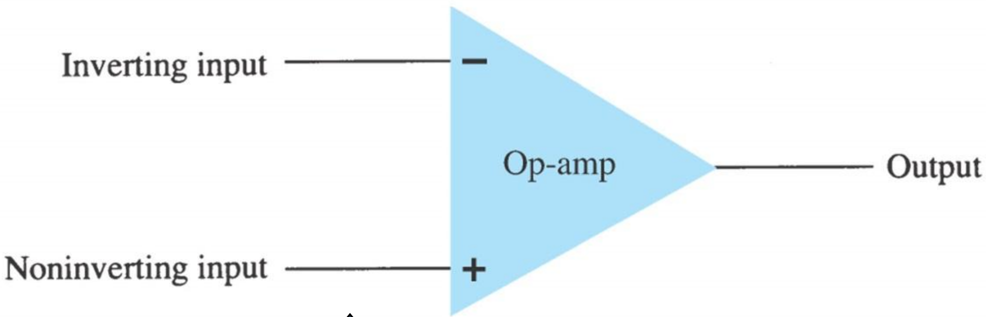


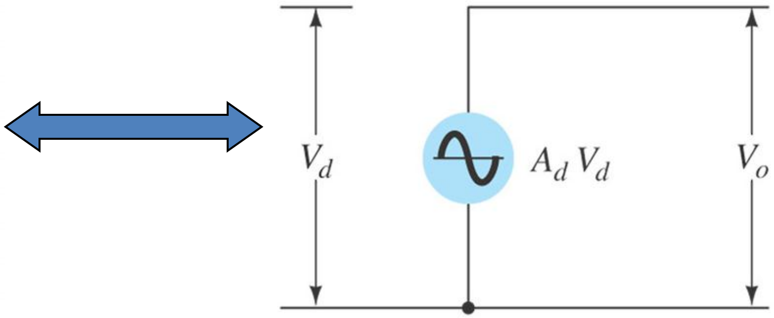
Constant-current circuit using Zener diode

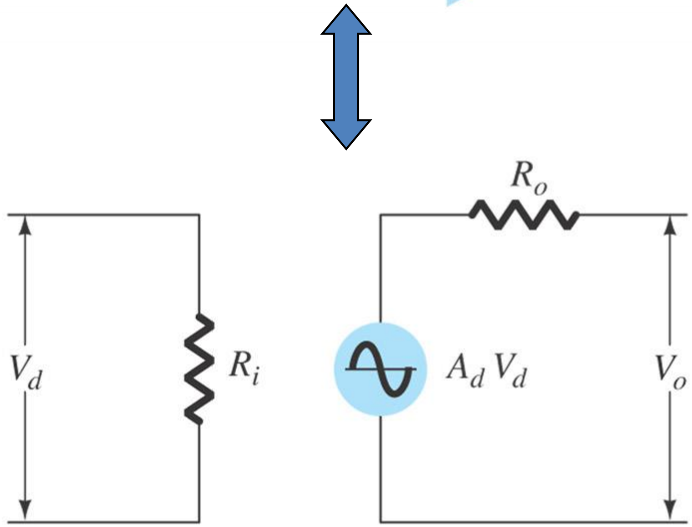
Use of Constant-Current Source



Op-Amp Basics







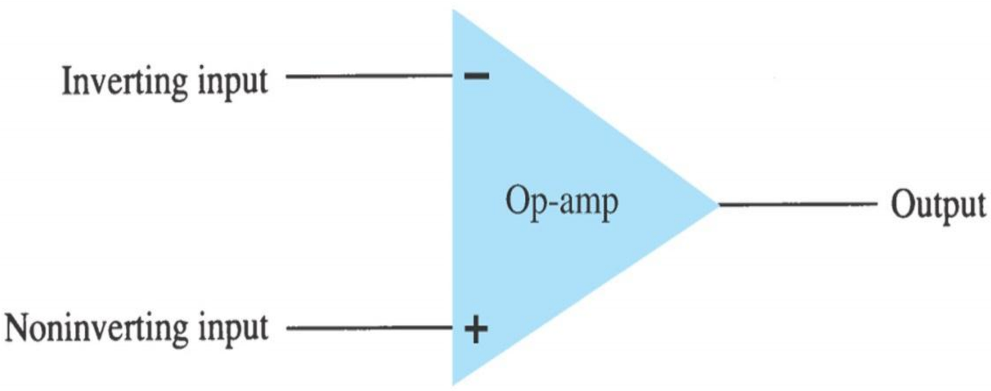
Ideal features of op-amp:

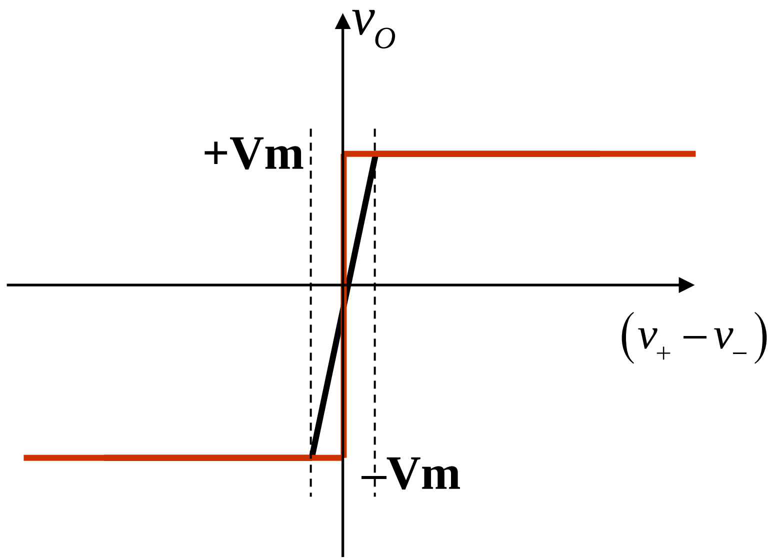
- $A_d = \infty$, $A_c = 0$
- $R_i = \infty$
- $R_o = 0$

Practical features of op-amp:

- very high gain A_d for differential input V_d (Open-Loop differential Gain)
- high input impedance R_i (typically a few meg-Ohms)
- low output impedance R_o (less than 100 Ω).

Op-Amp Basics





Ideal features of op-amp:

- $A_d = \infty$, $A_c = 0$
- $R_i = \infty$
- $R_o = 0$

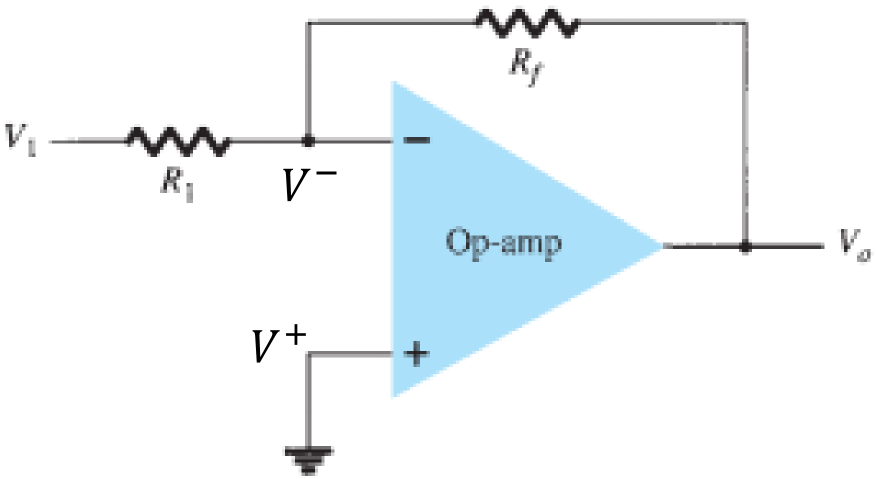
Virtual Short: $V^+ = V^-$

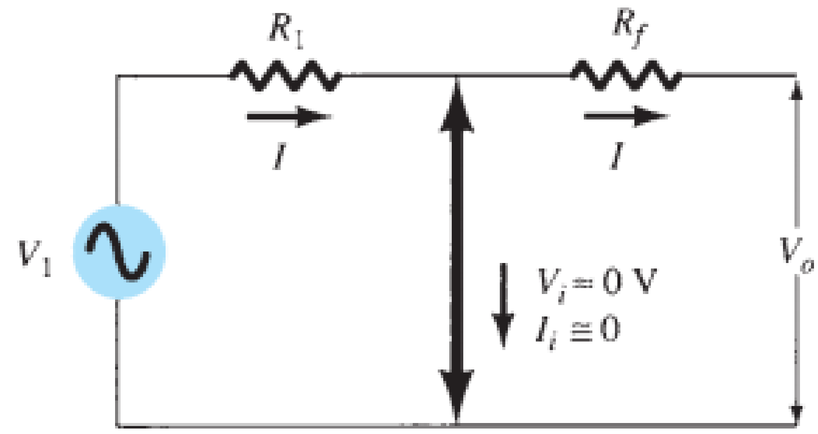
Virtual Open: $I^+ = I^- = 0$

Working at linear region →

circuit with negative feedback

Inverting Amplifier





Virtual Open $I^+ = I^- = 0$

Virtual Short $V^+ = V^-$

$V^+ = 0 \Longrightarrow V^+ = V^- = 0$ **Virtual Ground**

Inverting Amplifier

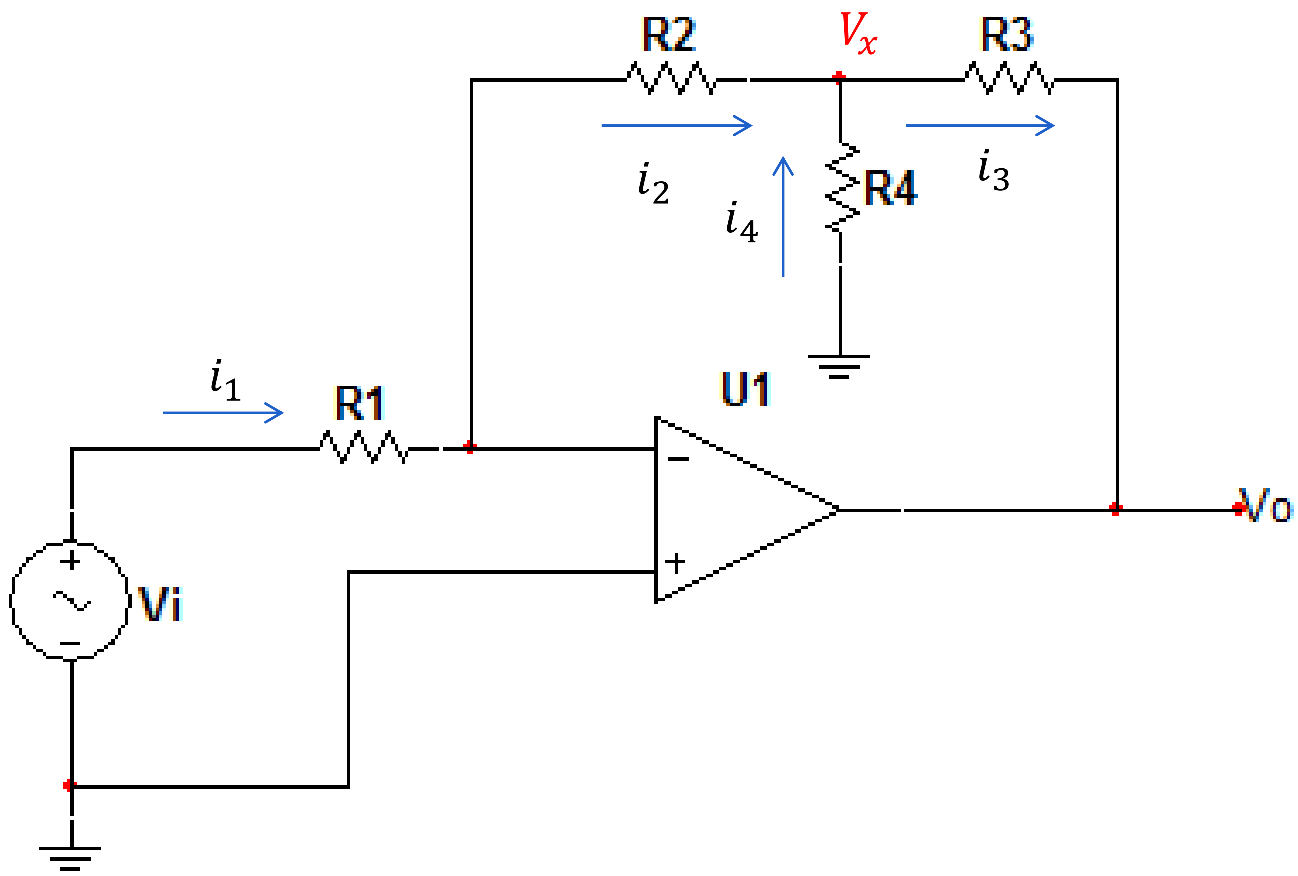
$$I = \frac{V_i}{R_1} = \frac{0 - V_o}{R_f} \qquad A_V = \frac{V_o}{V_i} = -\frac{R_f}{R_1}$$

The ratio of the overall output to input voltage is dependent only on the values of resistors R_1 *and* R_f

$$R_i = ? \qquad R_i = \frac{V_i}{I_i} = R_1$$

If $R_1 = R_f$ $\Rightarrow$ $A_V = -1$

Amplifier with a T-Network

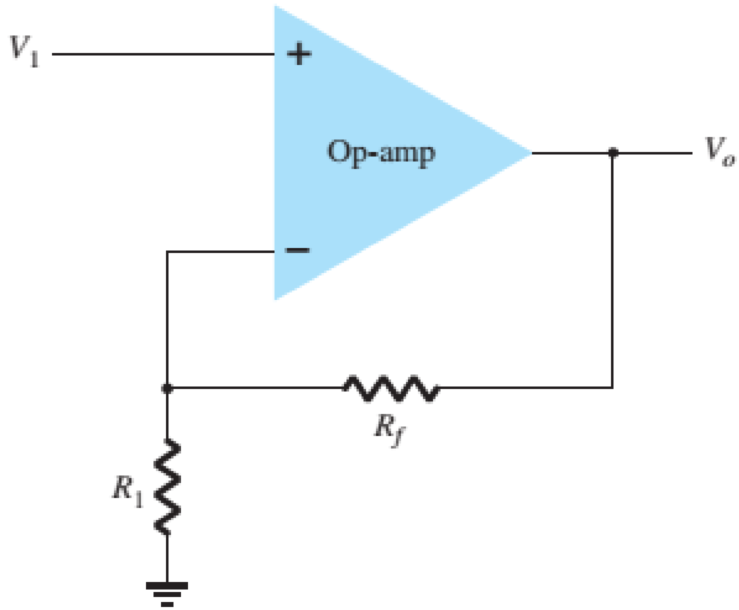


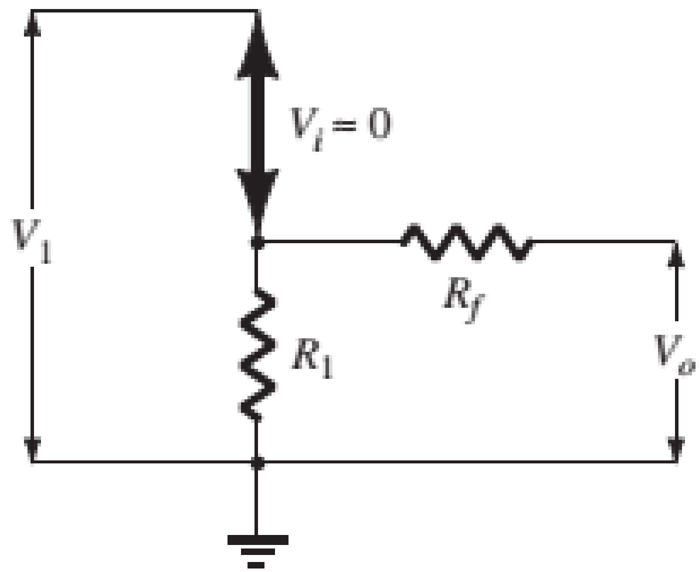
Exercise Problem

Design an ideal inverting op-amp with a T-network that has a closed-loop voltage gain of Av=-50, and an input resistance of 10kΩ. All resistors must be no larger than 50kΩ.

The amplifier with a T-network allows us to obtain a large gain using reasonably sized resistor.

Noninverting Amplifier



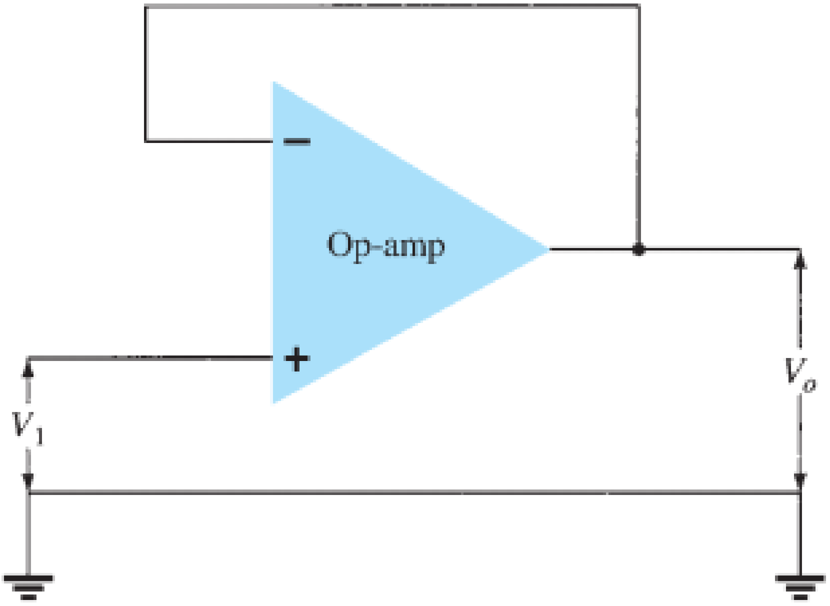


Virtual Open $I^+ = I^-$

Virtual Short $V^+ = V^-$

$$A_V = 1 + \frac{R_f}{R_1}$$

Unity Follower

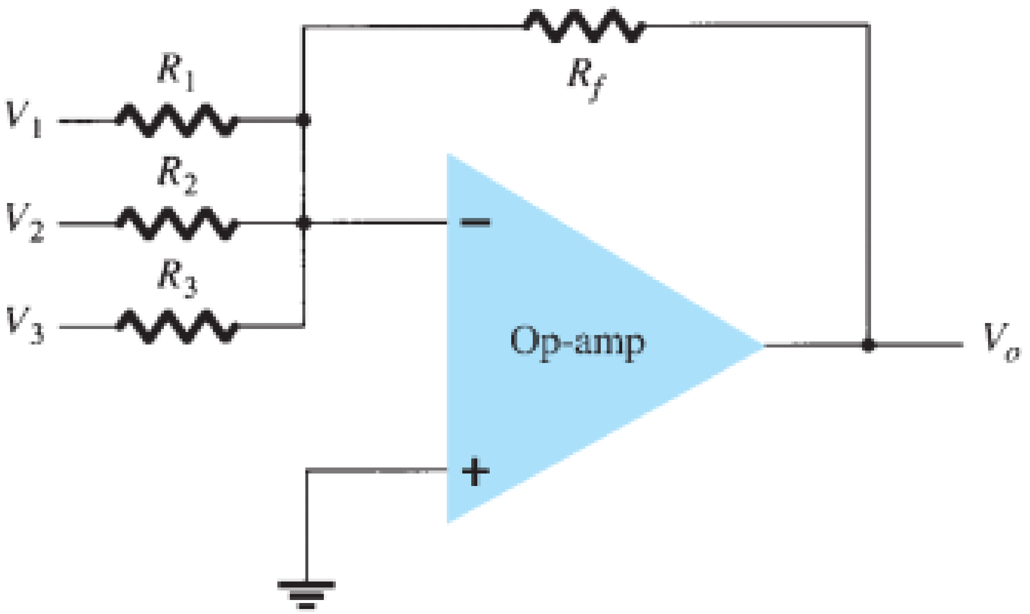


$$V_o = V_i$$

Problem-Solving Technique

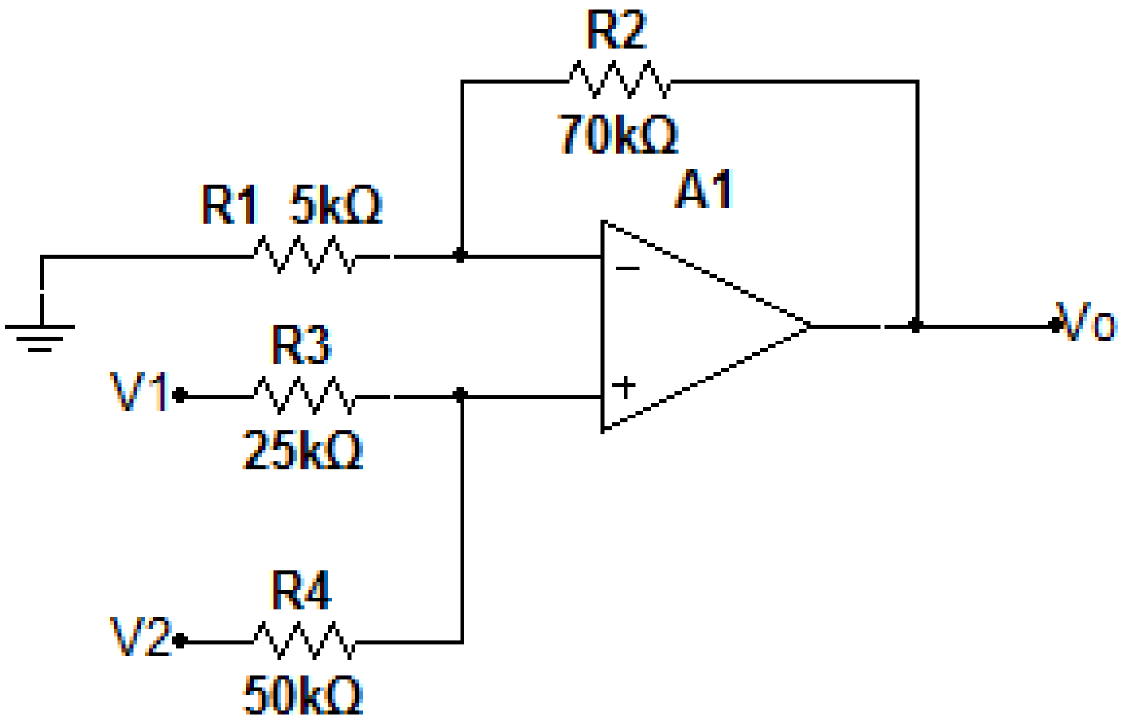
1. If the noninverting terminal of the op-amp is at ground potential, the the inverting terminal is at virtual ground. Sum currents at this node, assuming zero current enters the op-amp itself.
2. If the noninverting terminal of the op-amp is not at ground potential, then the inverting terminal voltage is equal to that at the noninverting terminal. Sum currents at the inverting terminal node, assuming zero current enters the op-amp itself.
3. For the ideal op-amp circuit, the output voltage is determined from either step 1 or step 2 above and is independent of any load connected to the output terminal.

Voltage Summing

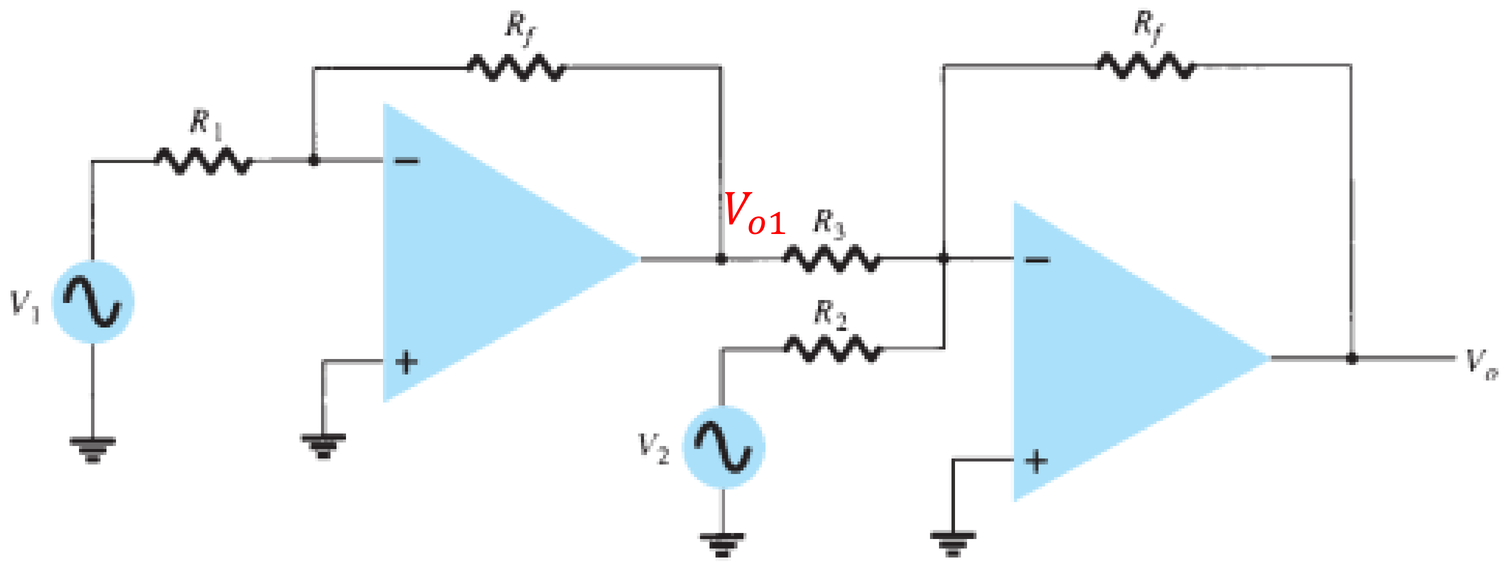


$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$

Exercise Problem

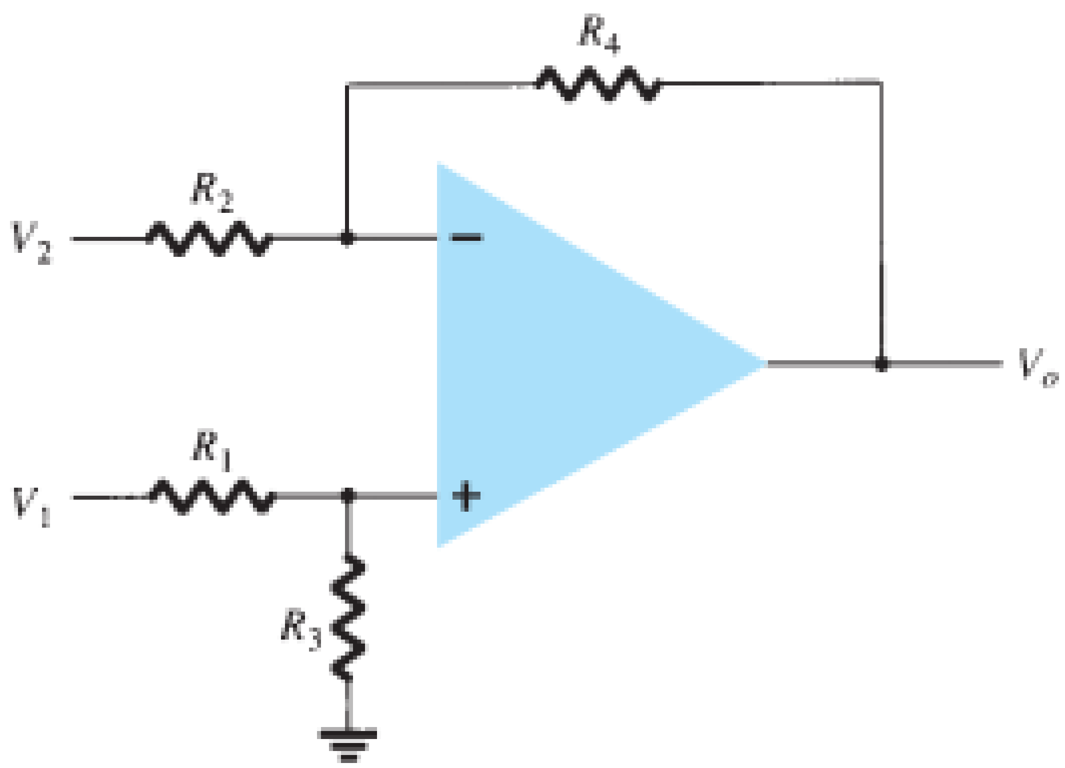


Voltage Subtraction



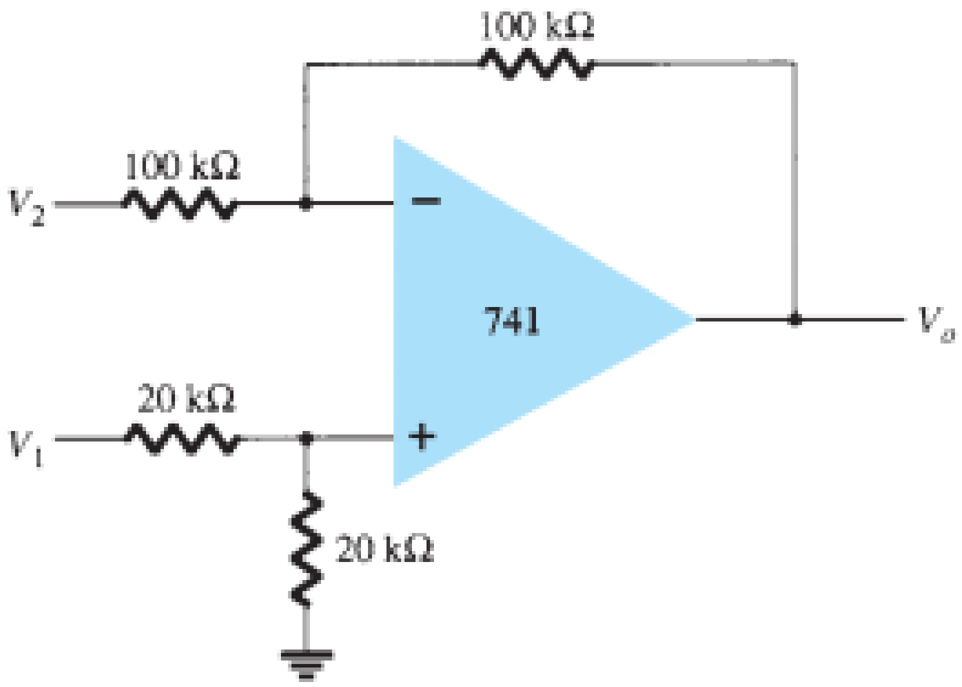
$$V_o = -\left(\frac{R_f}{R_2}V_2 - \frac{R_f}{R_3}\frac{R_f}{R_1}V_1\right)$$

Voltage Subtraction



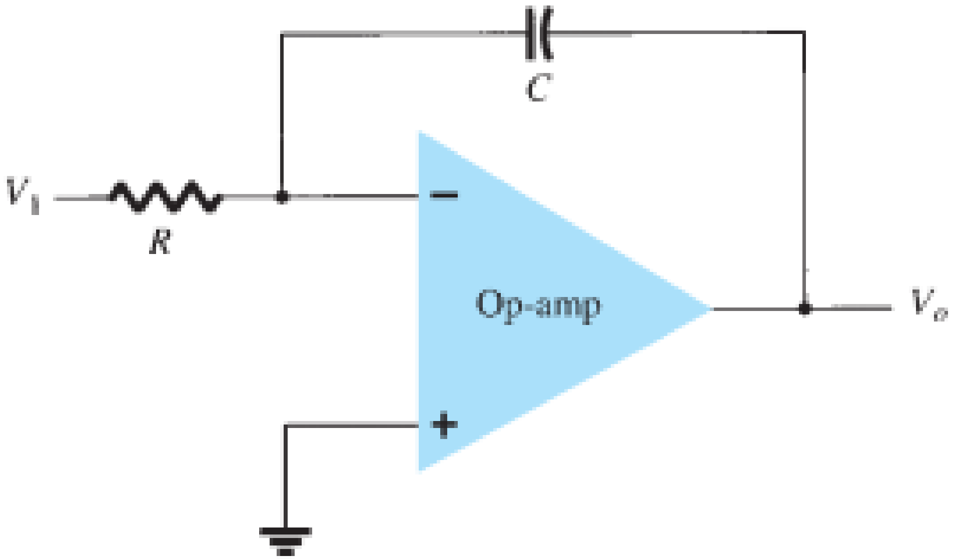
$$V_o = \frac{R_3}{R_1 + R_3}\frac{R_2 + R_4}{R_2}V_1 - \frac{R_4}{R_2}V_2$$

Example 11.3



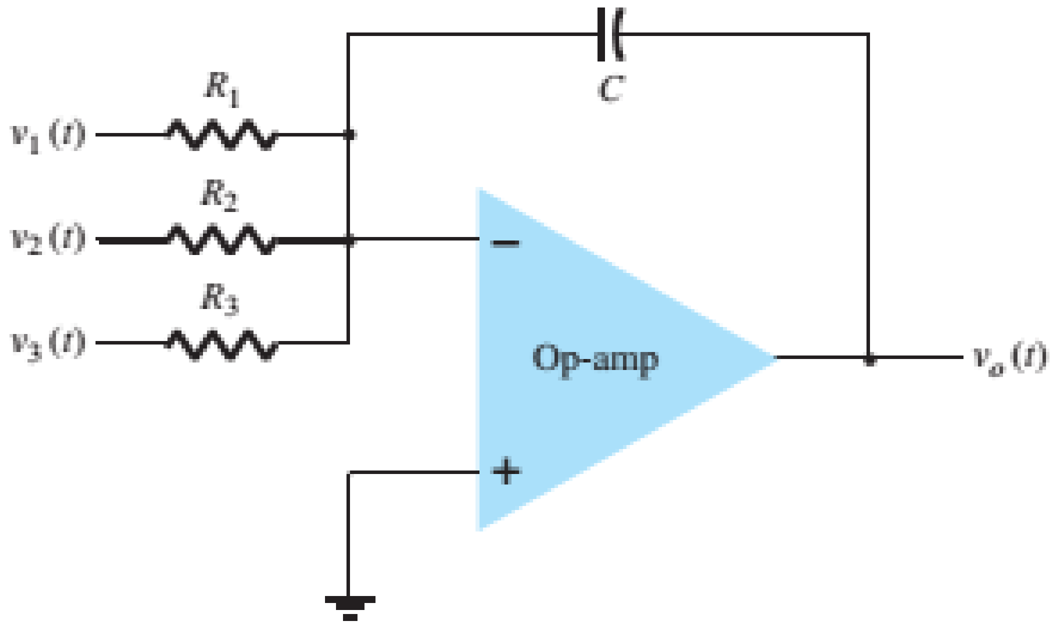
$$V_o = \left(\frac{20K\Omega}{20K\Omega + 20K\Omega}\right)\left(\frac{100K\Omega + 100K\Omega}{100K\Omega}\right)V_1 - \frac{100K\Omega}{100K\Omega}V_2 = V_1 - V_2$$

Integrator



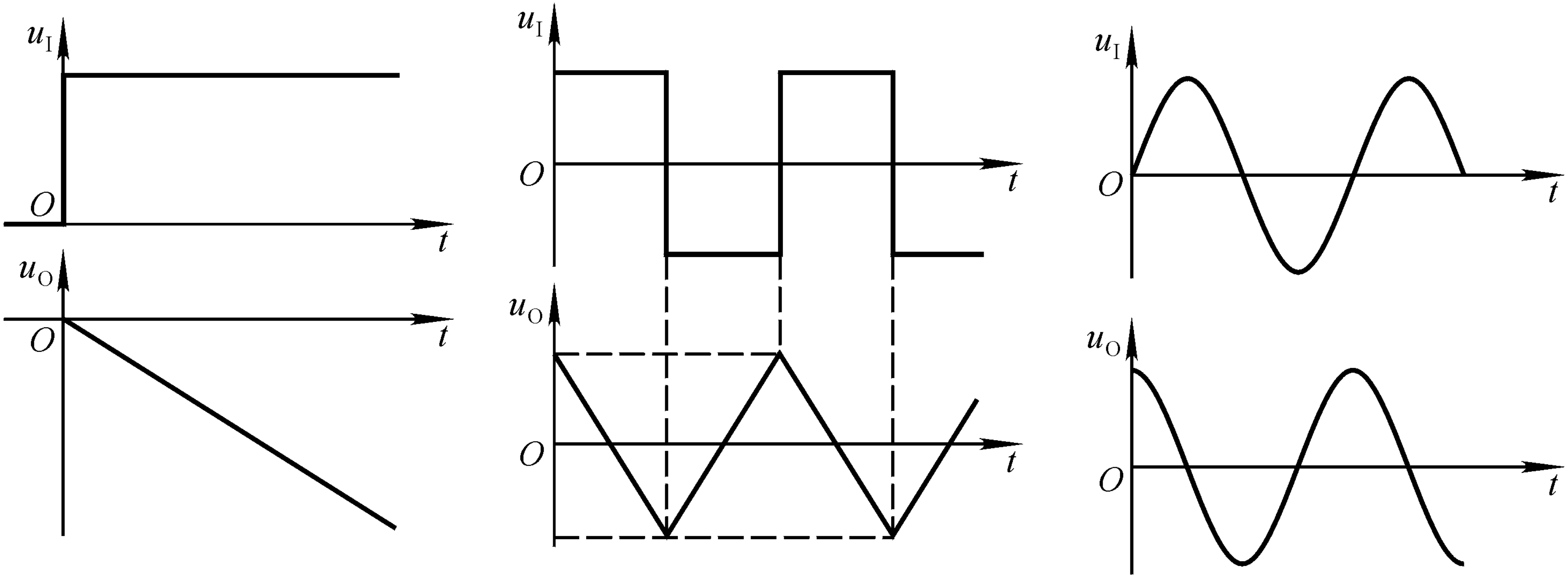
$$v_o(t) = -\frac{1}{RC}\int v_1(t)dt$$

Integrator



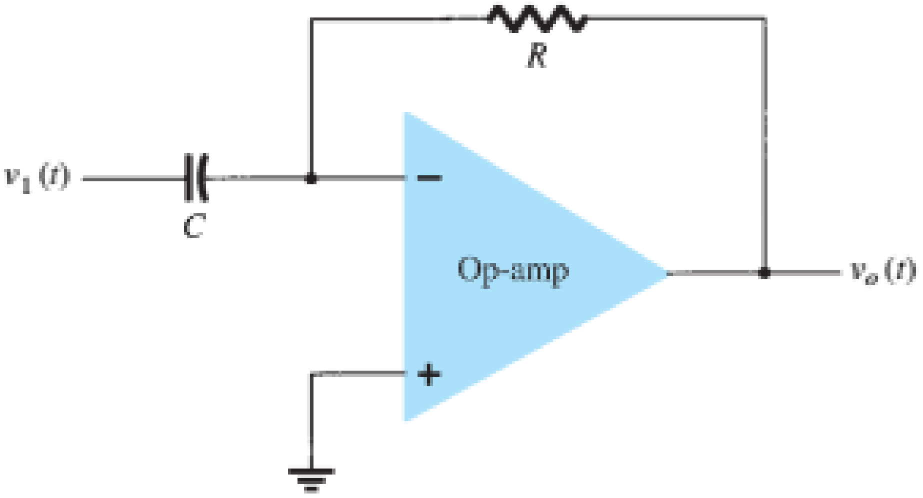
$$v_o(t) = -\left[\frac{1}{R_1C}\int v_1(t)\,dt + \frac{1}{R_2C}\int v_2(t)\,dt + \frac{1}{R_3C}\int v_3(t)\,dt\right]$$

Exercise



(a) (b) (c)

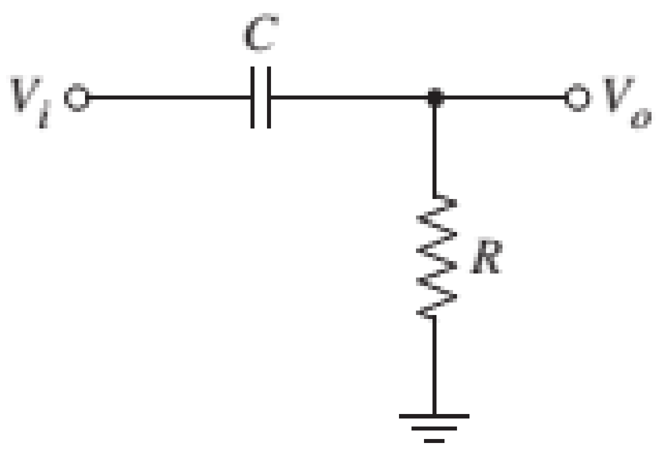
Differentiator

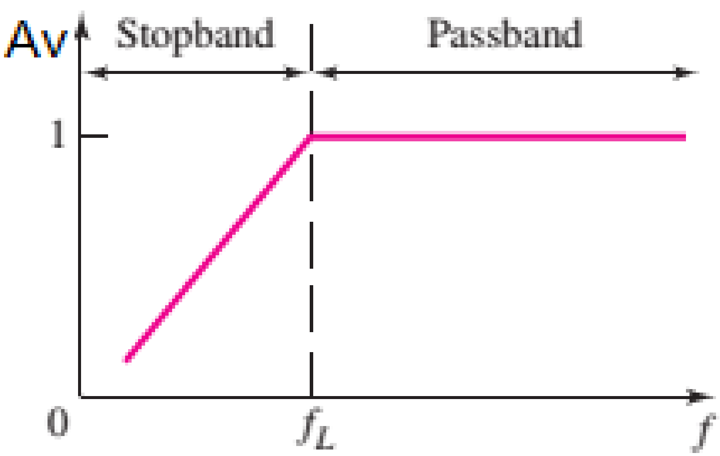


$$v_o(t) = -RC\frac{dv_1(t)}{dt}$$

Active Filter

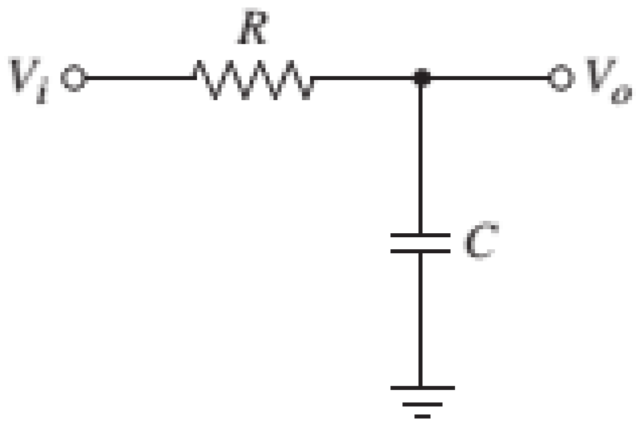
- The word ***filter*** refers to the process of removing undesired portions of the frequency spectrum.

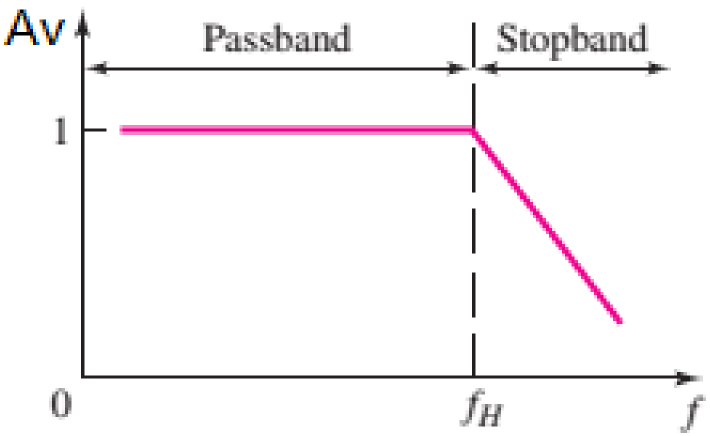




Active Filter

- ➢ The word ***filter*** refers to the process of removing undesired portions of the frequency spectrum.
- ➢ The word ***active*** mplies the use of one or more active devices, usually an operational amplifier,in the filter circuit.



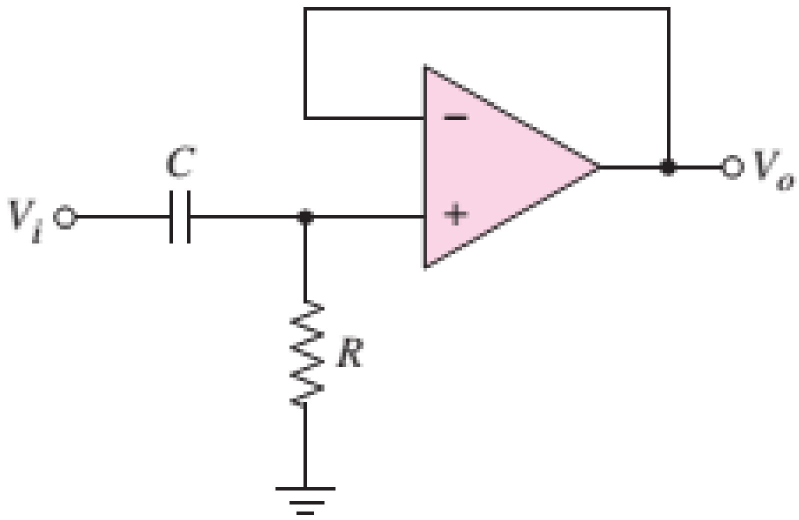


Active Filter

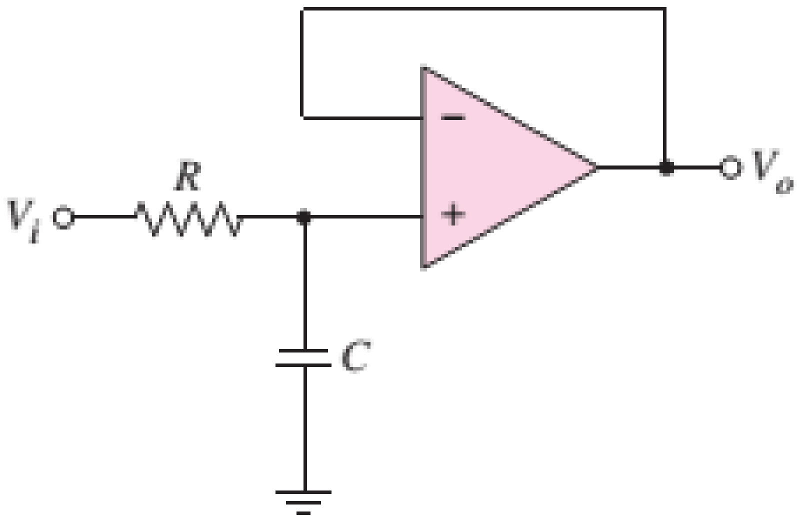
Two advantages of active filters over passive filters are:

- The maximum gain or the maximum value of the transfer function may be greater than unity.
- The loading effect is minimal, which means that the output response of the filter is essentially independent of the load driven by the filter.

Active Filter



(a)



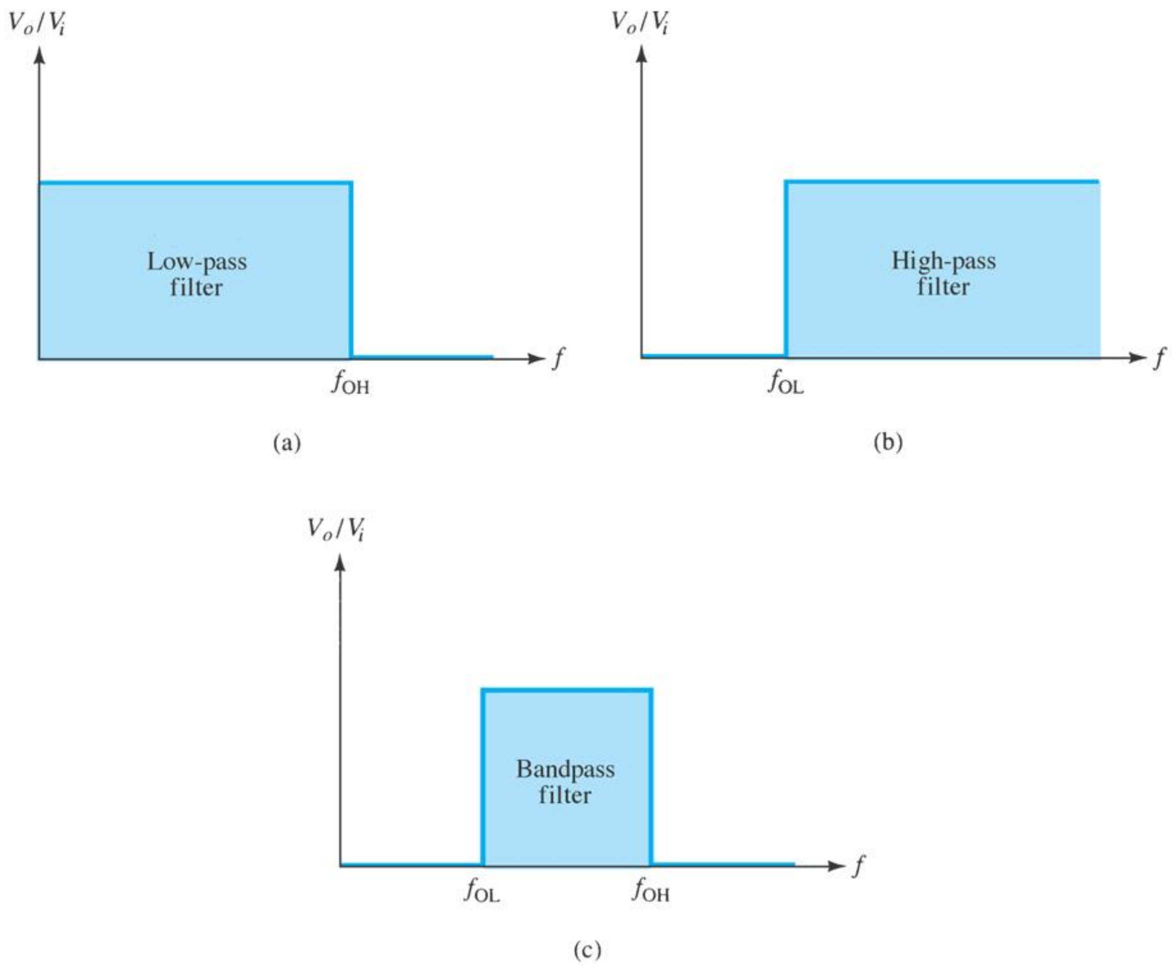
(b)

(a) High-pass filter with voltage follower (b) Low-pass filter with voltage follower

$$f_L = \frac{1}{2\pi RC}$$

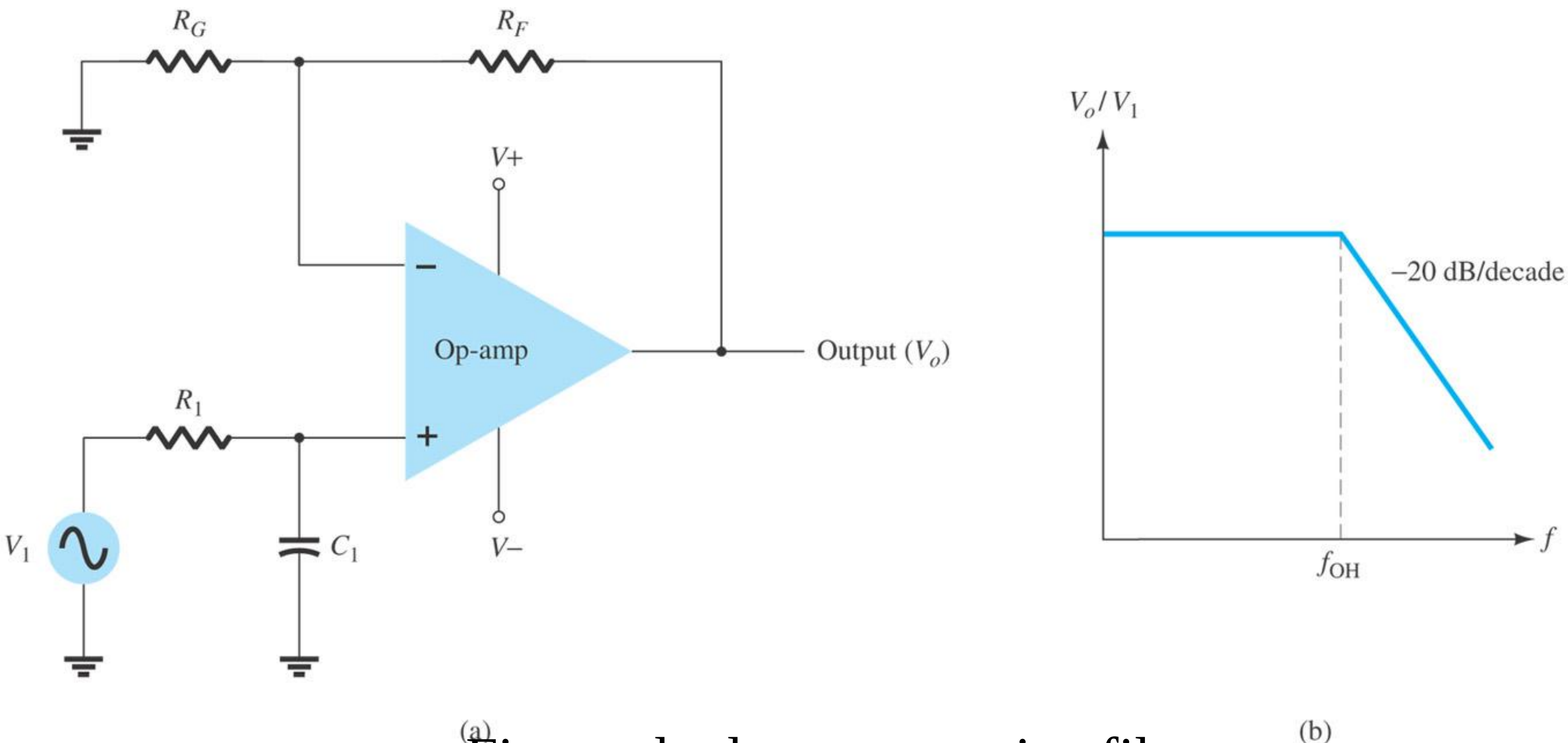
$$f_H = \frac{1}{2\pi RC}$$

Active Filter



Ideal filter response: **(a) low-pass**; **(b) high-pass**; **(c) bandpass**.

Active Filter

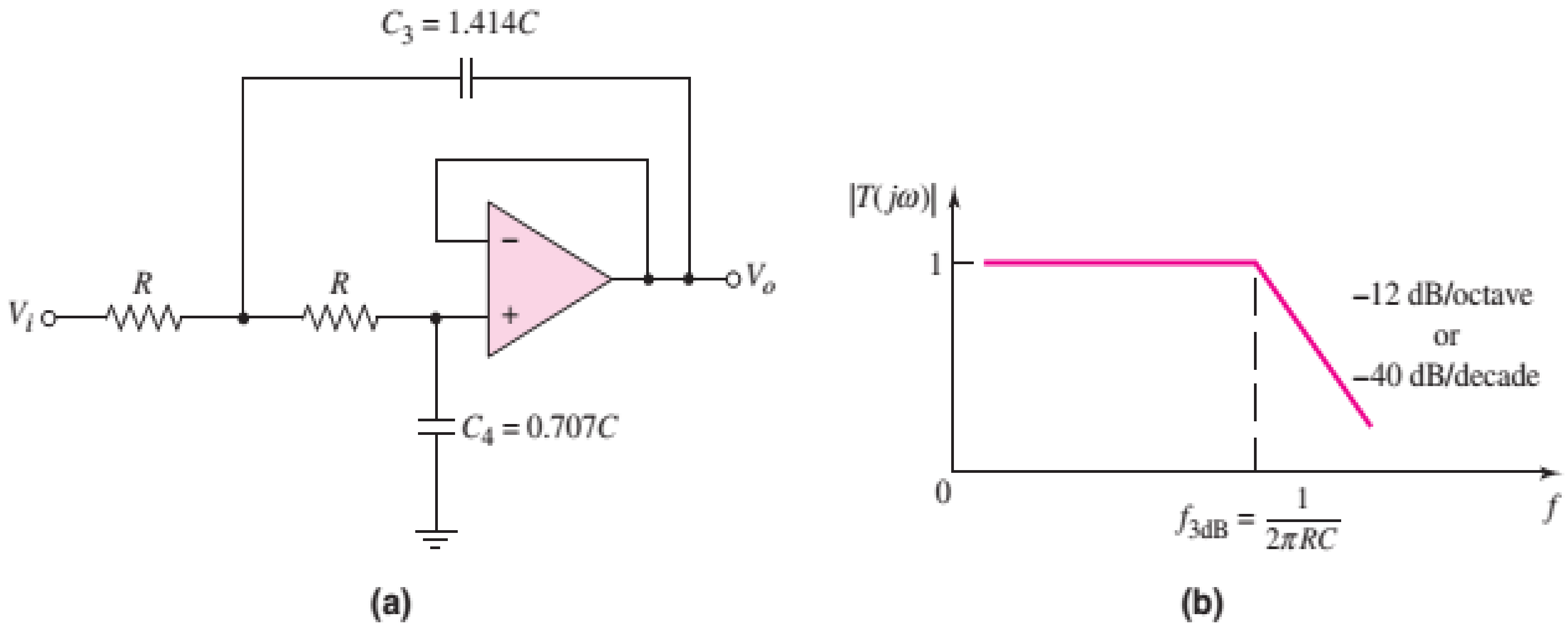


First-order low-pass active filter

$$f_{OH} = \frac{1}{2\pi R_1 C_1}$$

$$A_v = 1 + \frac{R_F}{R_G}$$

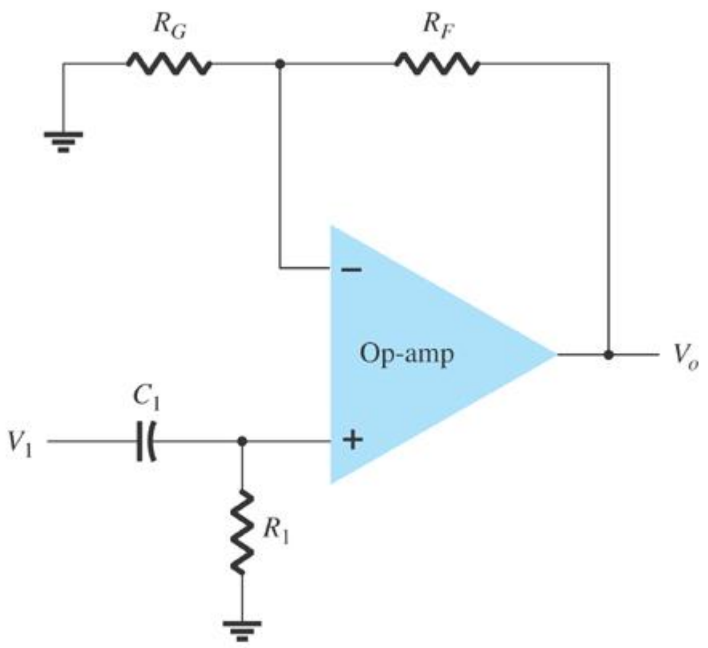
Active Filter

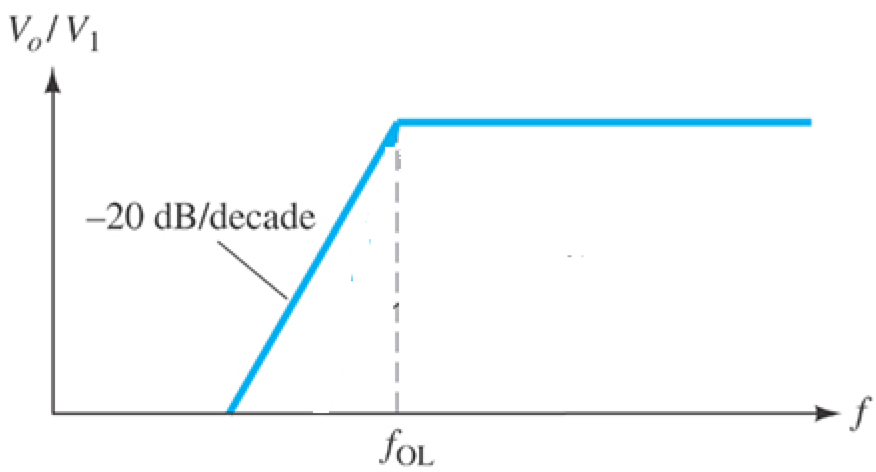


Second-order low-pass active filter

The roll-off can be made steeper by adding more RC networks.

Active Filter

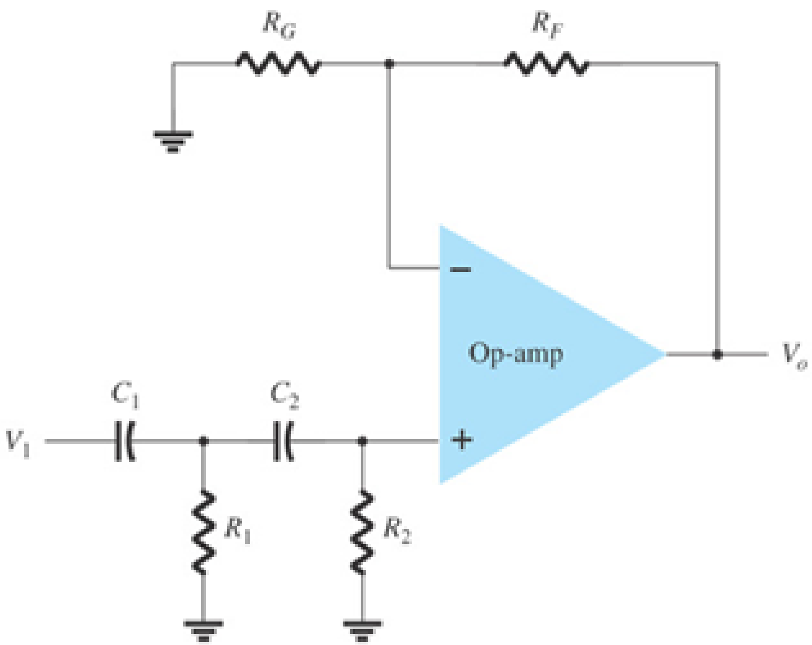


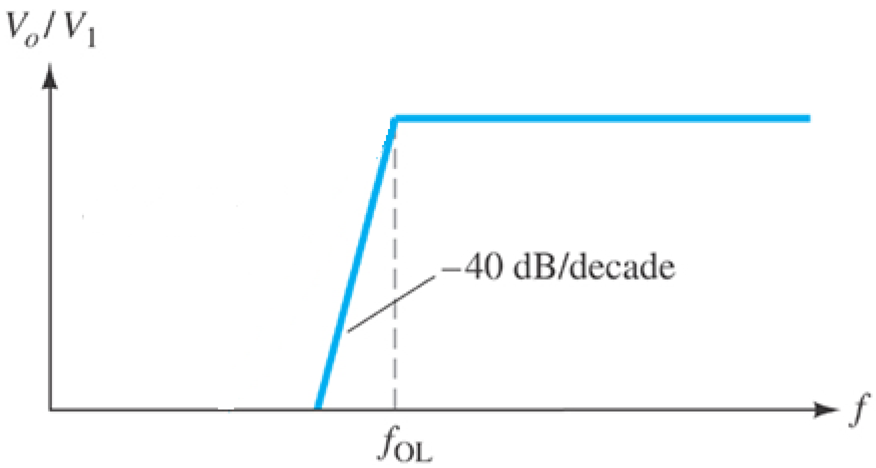


$$f_{OL} = \frac{1}{2\pi R_1 C_1}$$

$$A_v = 1 + \frac{R_F}{R_G}$$

Active Filter



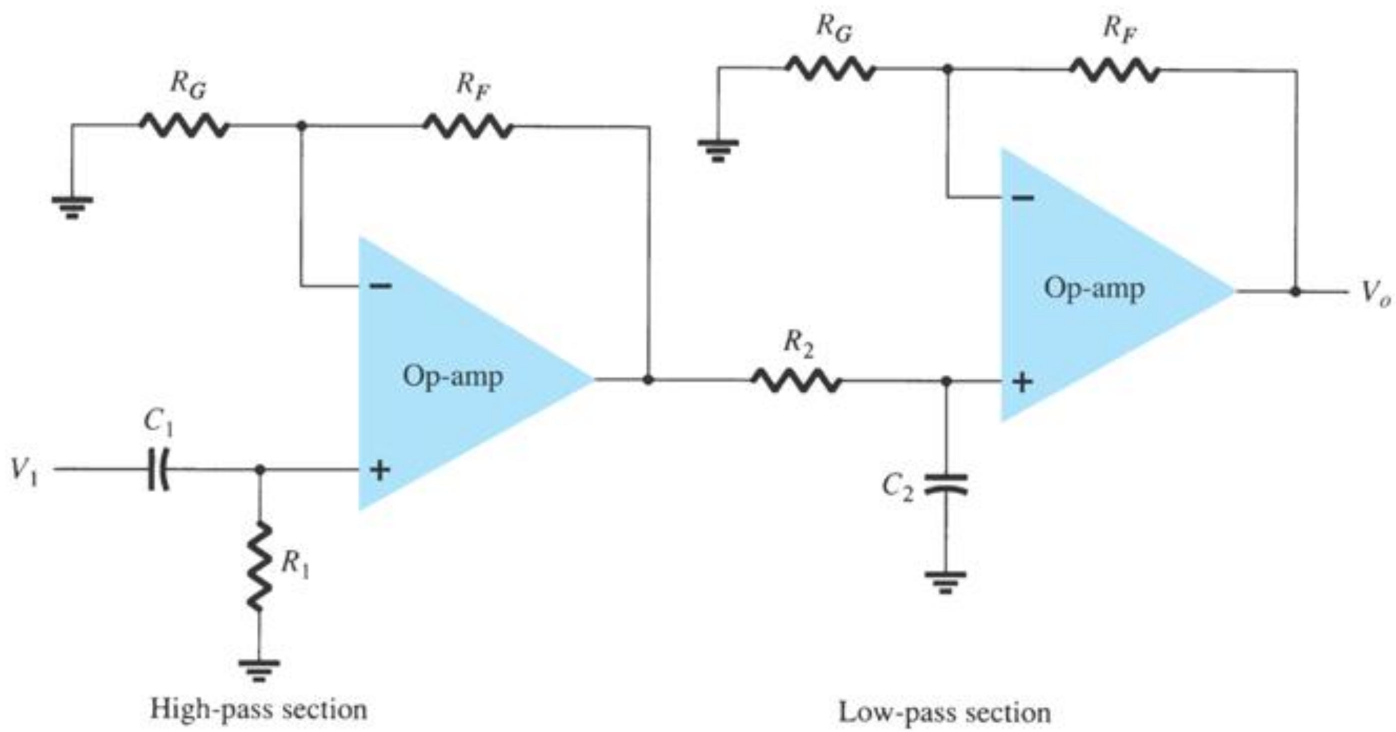


$$R_1 = R_2, C_1 = C_2$$

$$f_{OH} = \frac{1}{2\pi R_1 C_1}$$

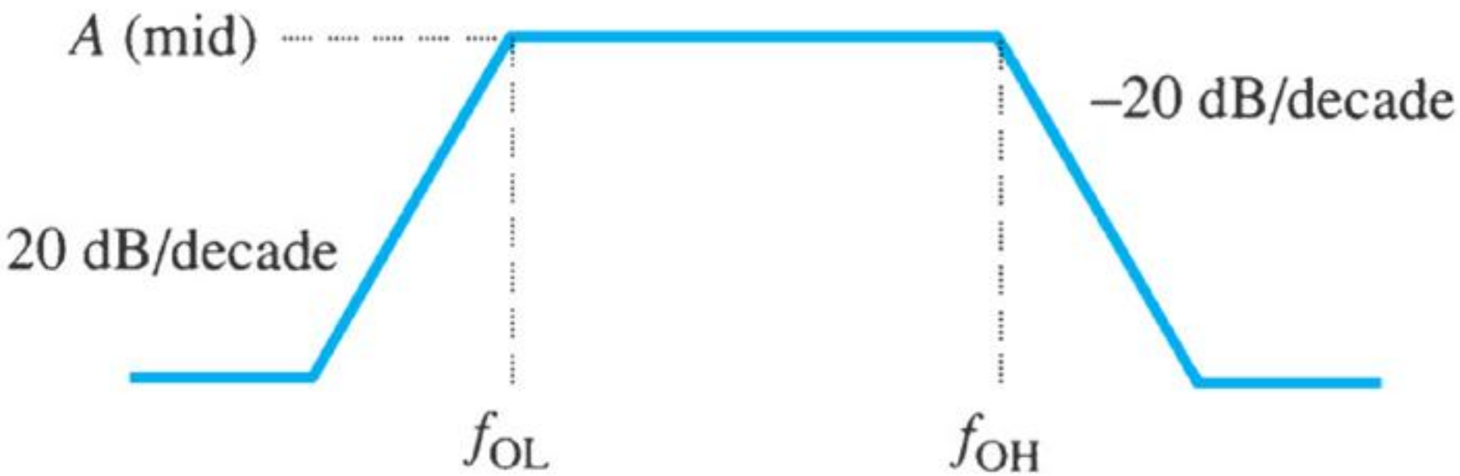
$$A_v = 1 + \frac{R_F}{R_G}$$

Active Filter

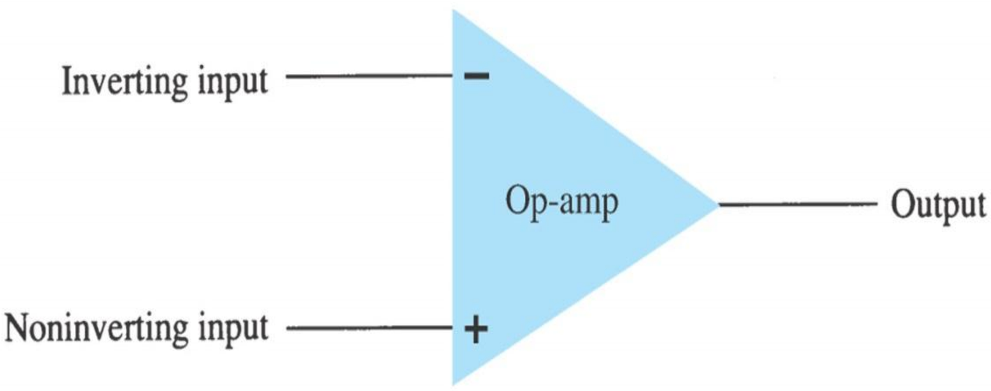


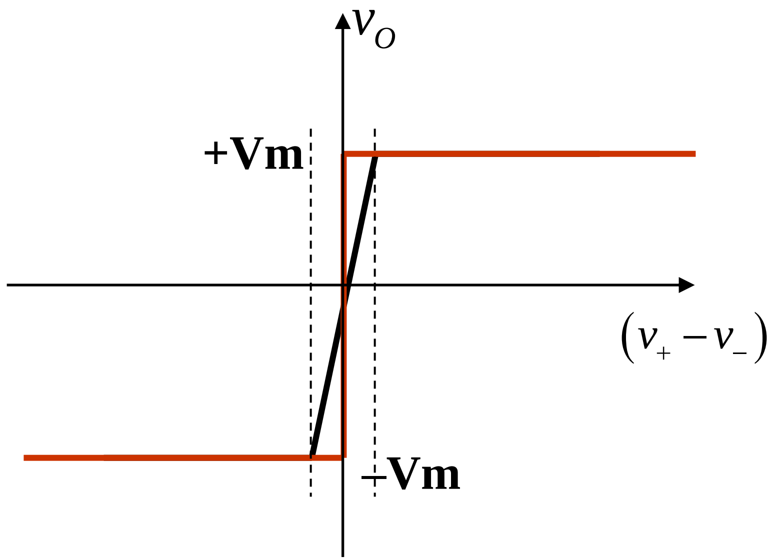
There are two cutoff frequencies: upper and lower. They can be calculated using the same low-pass cutoff and high-pass cutoff frequency formulas in the appropriate sections.

Active Filter



Comparator Unit Operation





Ideal features of op-amp:

- $A_d = \infty$, $A_c = 0$
- $R_i = \infty$
- $R_o = 0$

$$v_+ > v_- \longrightarrow v_O = +v_{OM}$$

$$v_+ < v_- \longrightarrow v_O = -v_{OM}$$

Schmitt Trigger

Op-Amp Specifications

DC-Offset Parameters

Even when the input voltage is zero, an op-amp can have an output **offset**. The following can cause this offset:

- Input offset voltage
- Input offset current
- Input offset voltage *and* input offset current
- Input bias current

Op-Amp Specifications

Frequency Parameters

An op-amp is a wide-bandwidth amplifier. The following factors affect the bandwidth of the op-amp:

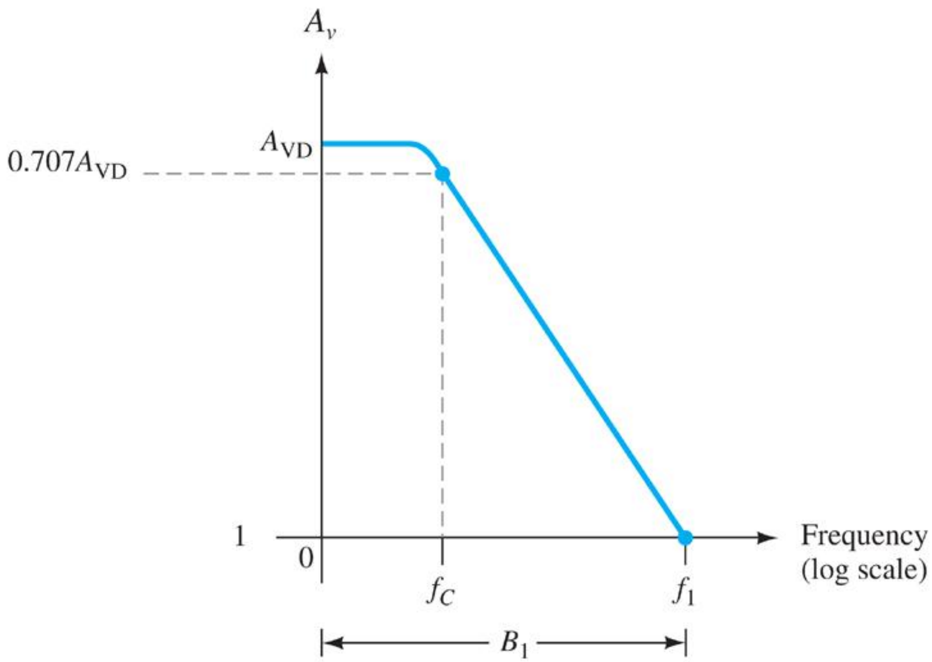
Gain

Slew rate

Op-Amp Specifications

Gain and Bandwidth

The op-amp's high frequency response is limited by its internal circuitry. The plot shown is for an open loop gain (A_{OL} or A_{VD}). This means that the op-amp is operating at the highest possible gain with no feedback resistor.



$$f_1 = A_{VD} f_C$$

In the open loop mode, an op-amp has a narrow bandwidth. The bandwidth widens in closed-loop mode, but the gain is lower.

Op-Amp Specifications

Slew Rate (SR)

Slew rate (SR): The maximum rate at which an op-amp can change output without distortion.

$$SR = \frac{\Delta V_o}{\Delta t} \quad V/\mu s$$

The SR rating is listed in the specification sheets as the V/μs rating.

Op-Amp Specifications