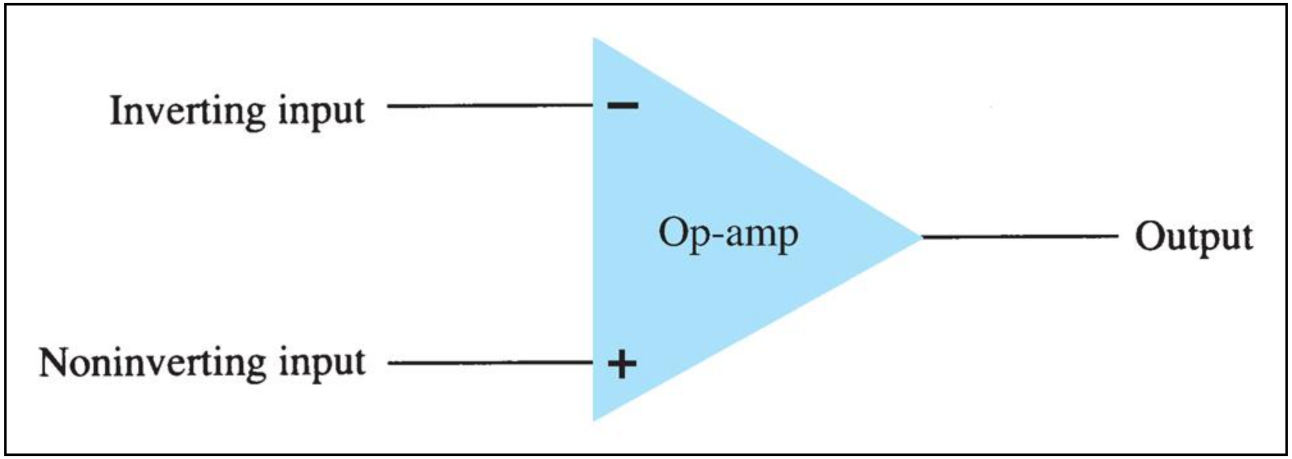
Operational Amplifiers

Boylestad

Chapter 10

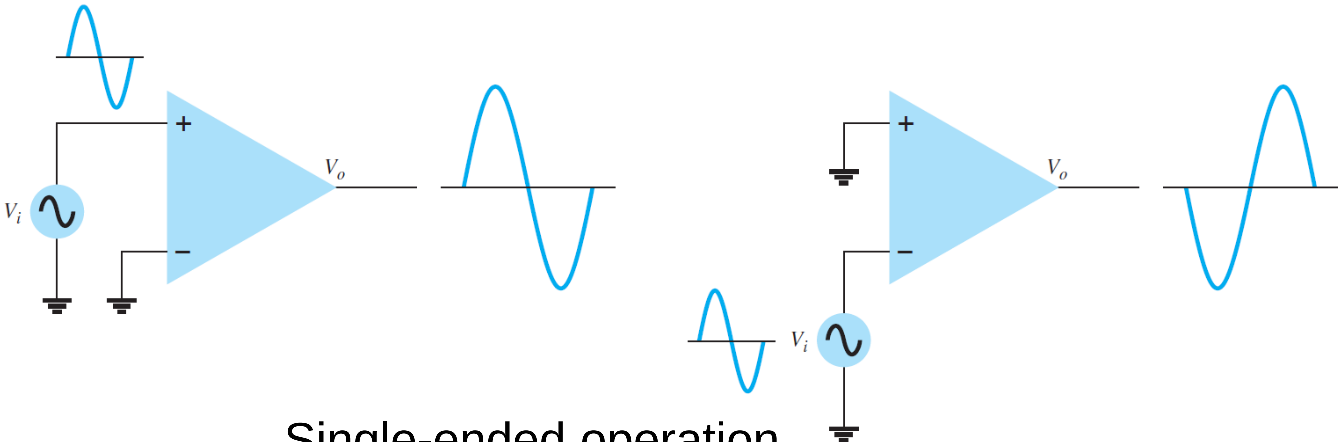
Operational Amplifier Basics



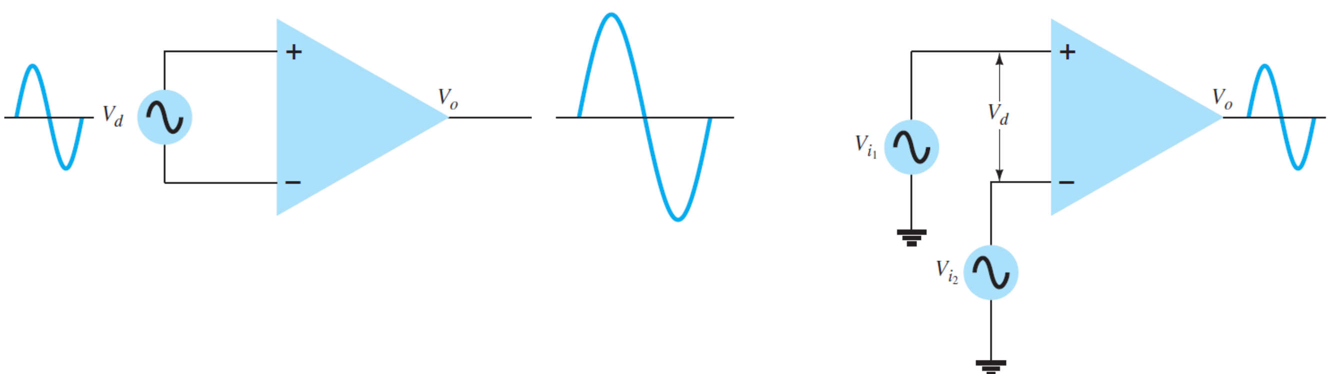
Operational amplifier (Op-amp): A high gain differential amplifier with a high input impedance (typically in MΩ) and low output impedance (less than 100Ω).

Note the op-amp has two inputs and one output.

Op-amp Operation Types

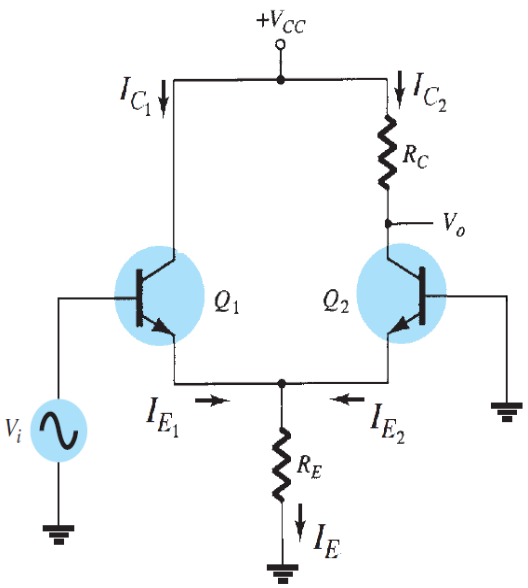


Single-ended operation

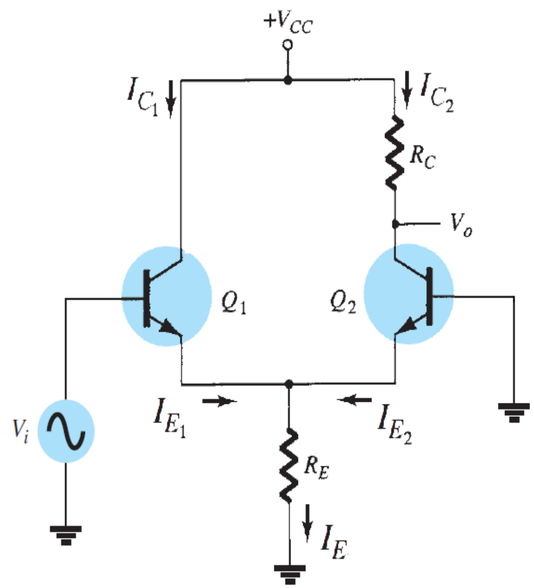


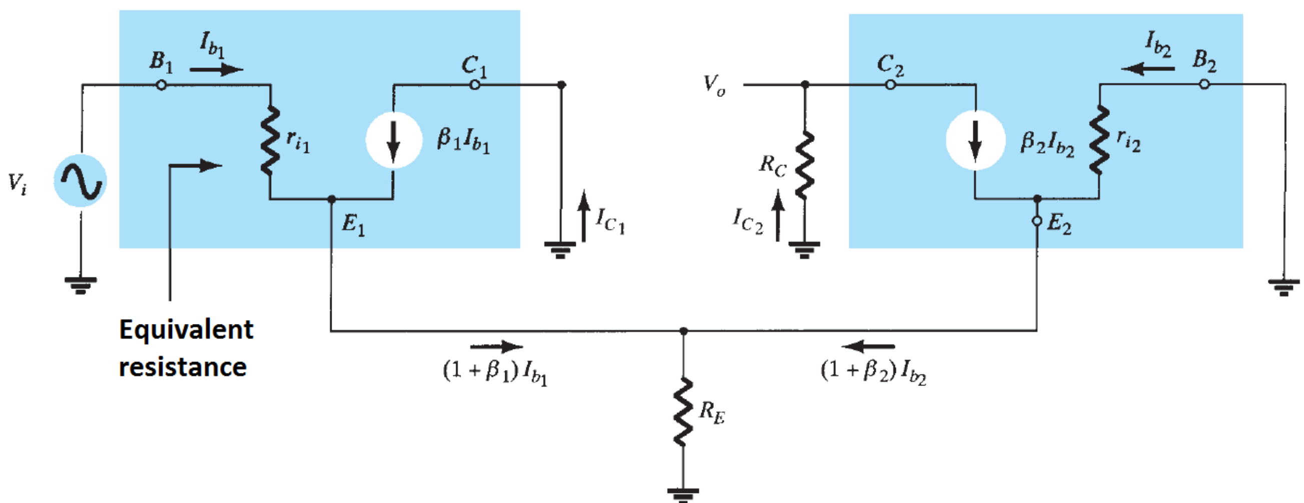
Double-ended (differential) operation

Differential Amplifiers

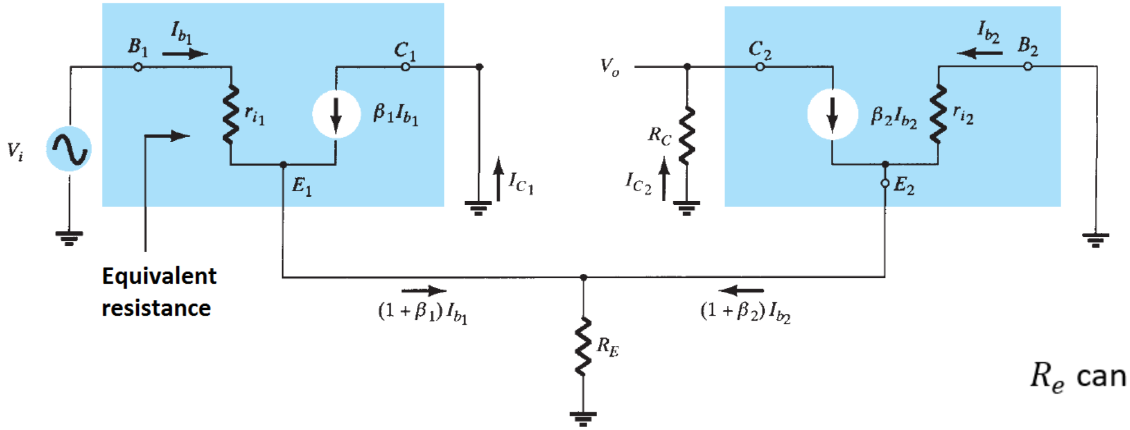


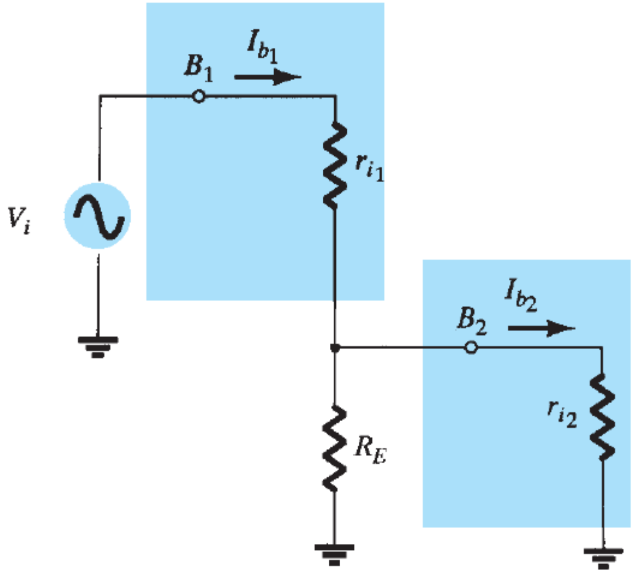
Differential Amplifiers





Differential Amplifiers





R_e can be neglected if $R_e \gg \beta r_e$

$$I_{b_1} = I_{b_2} = I_b \text{ (matched)}$$

$$\beta_1 = \beta_2 = \beta \text{ (matched)}$$

$$I_{c_1} = I_{c_2} = I_c \text{ (matched)}$$

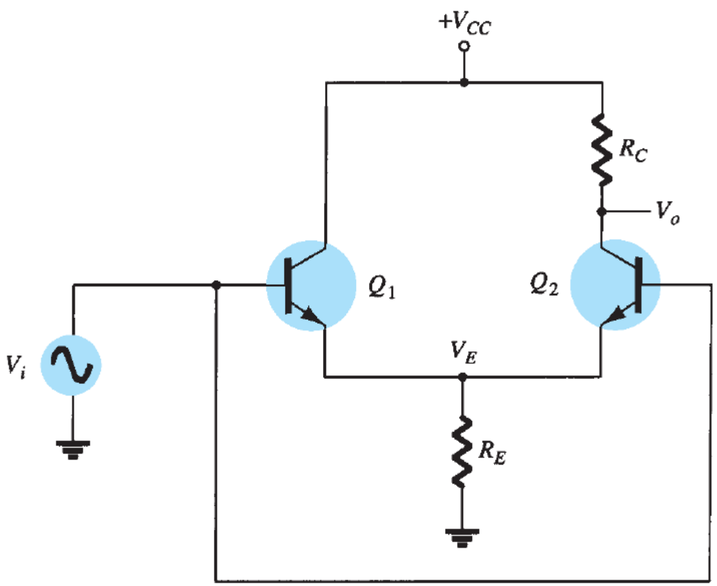
$$V_i \approx I_b \beta r_e + I_b \beta r_e = 2 I_b \beta r_e$$

$$V_o = -I_c R_C \quad \text{but} \quad I_c = \beta I_b$$

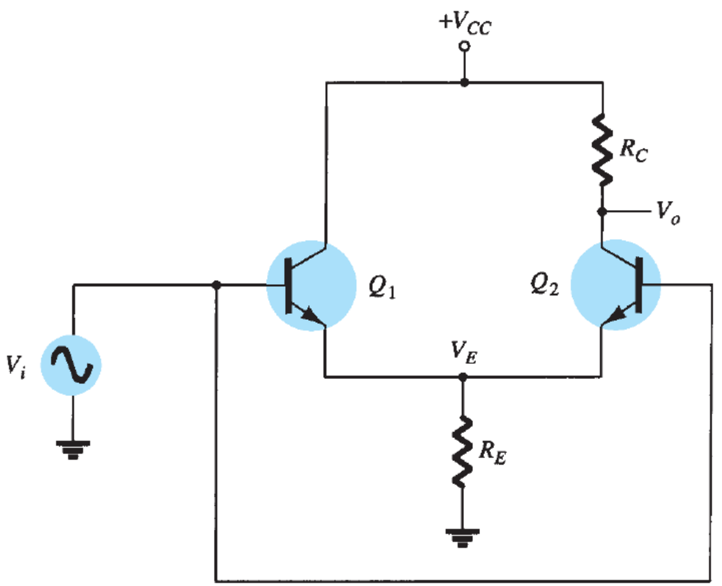
$$V_o = -\beta I_b R_C$$

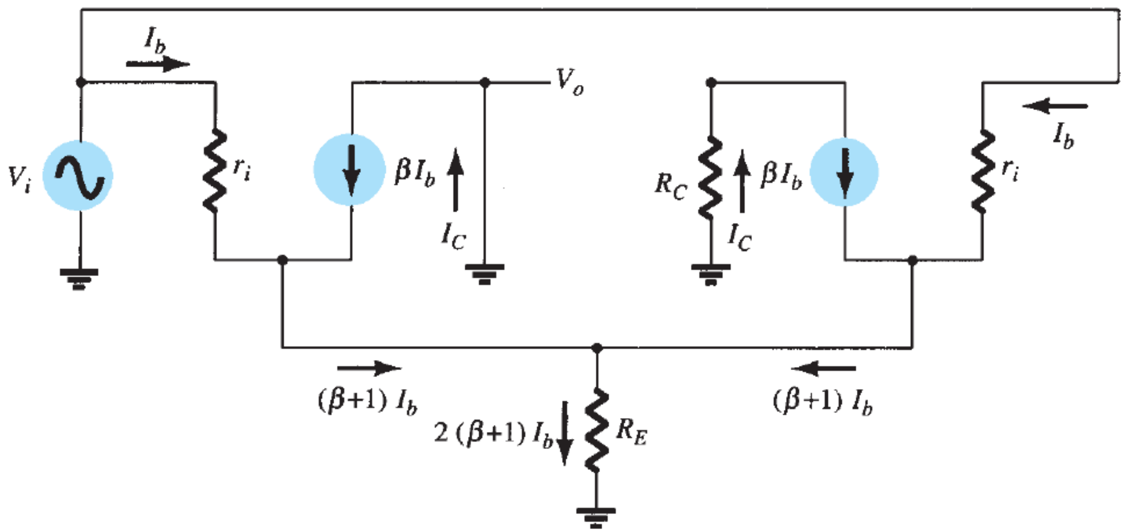
Differential voltage gain $A_{v_d} = -\frac{R_C}{2r_e}$

Differential Amplifiers

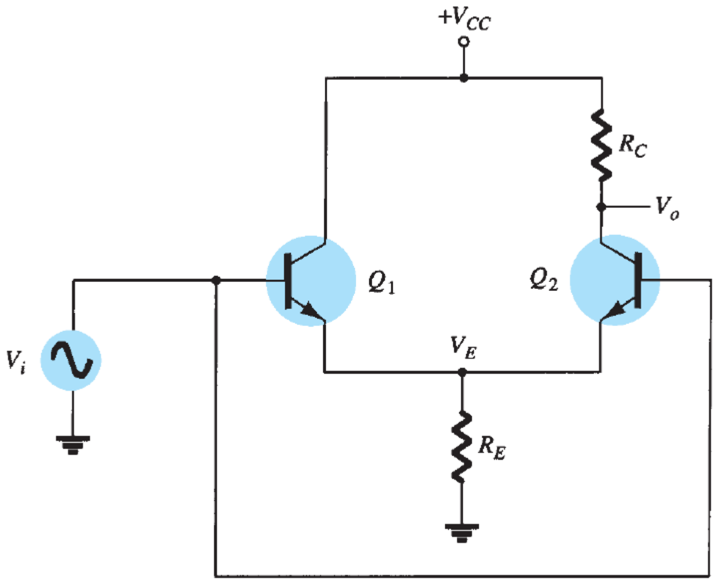


Differential Amplifiers





Differential Amplifiers



$$V_i \approx I_b \beta r_e + 2(\beta + 1) I_b R_E$$

$$V_i \approx I_b \beta (r_e + 2R_E)$$

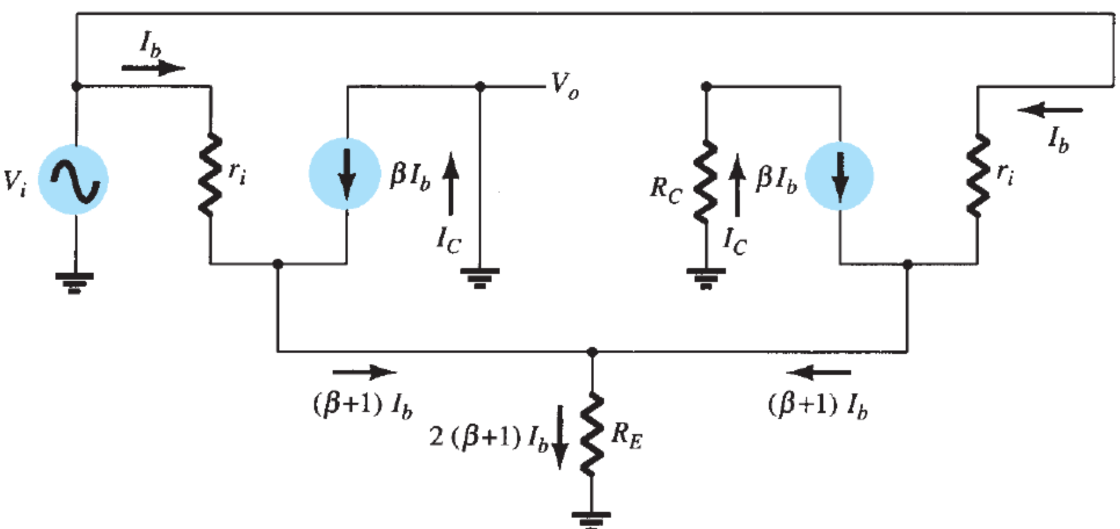
$$V_o = -I_c R_c = -\beta I_b R_c$$

$$A_{v_c} = \frac{V_o}{V_i} = -\frac{\beta I_b R_c}{\beta I_b (r_e + 2R_E)}$$

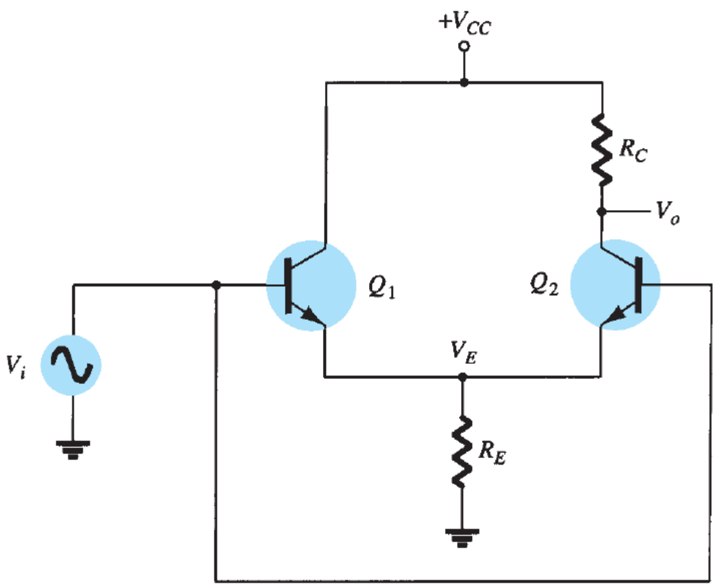
Common-mode voltage gain $A_{v_c} = -\frac{R_C}{r_e + 2R_E}$

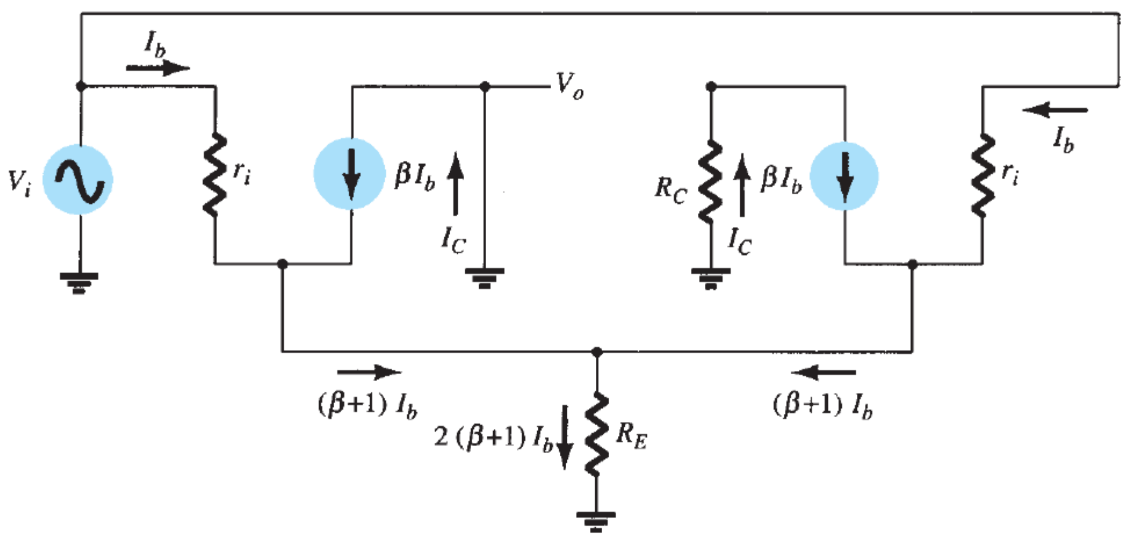
Remember $A_{v_d} = -\frac{R_C}{2r_e}$

$$|A_{v_d}| \gg |A_{v_c}|$$



Differential Amplifiers





$$V_i \approx I_b \beta r_e + 2(\beta + 1) I_b R_E$$

$$V_i \approx I_b \beta (r_e + 2R_E)$$

$$V_o = -I_c R_c = -\beta I_b R_c$$

$$A_{v_c} = \frac{V_o}{V_i} = -\frac{\beta I_b R_c}{\beta I_b (r_e + 2R_E)}$$

Common-mode voltage gain $A_{v_c} = -\frac{R_C}{r_e + 2R_E}$

Remember $A_{v_d} = -\frac{R_C}{2r_e}$

$$|A_{v_d}| \gg |A_{v_c}|$$

The circuit amplifies the difference but suppresses the common signal

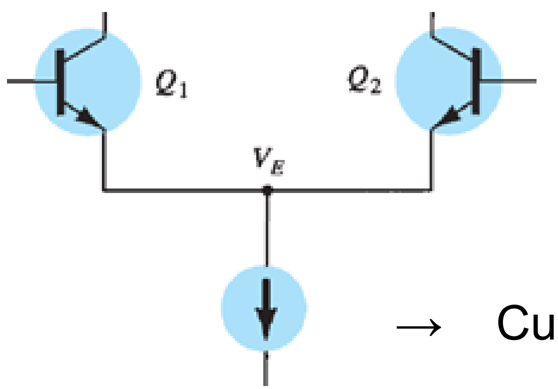
Increasing R_E

To decrease the common-mode voltage gain:

$$A_{v_c} = -\frac{R_C}{r_e + 2R_E}$$

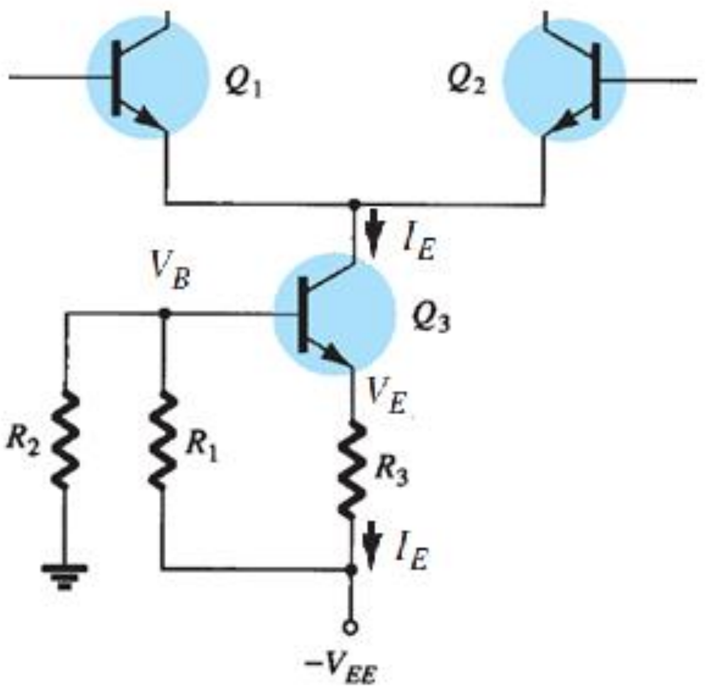
We should increase R_E

To increase R_E we can add a current source instead of R_E



→ Current source → $R_E \to \infty$

Increasing R_E – Constant Current Source

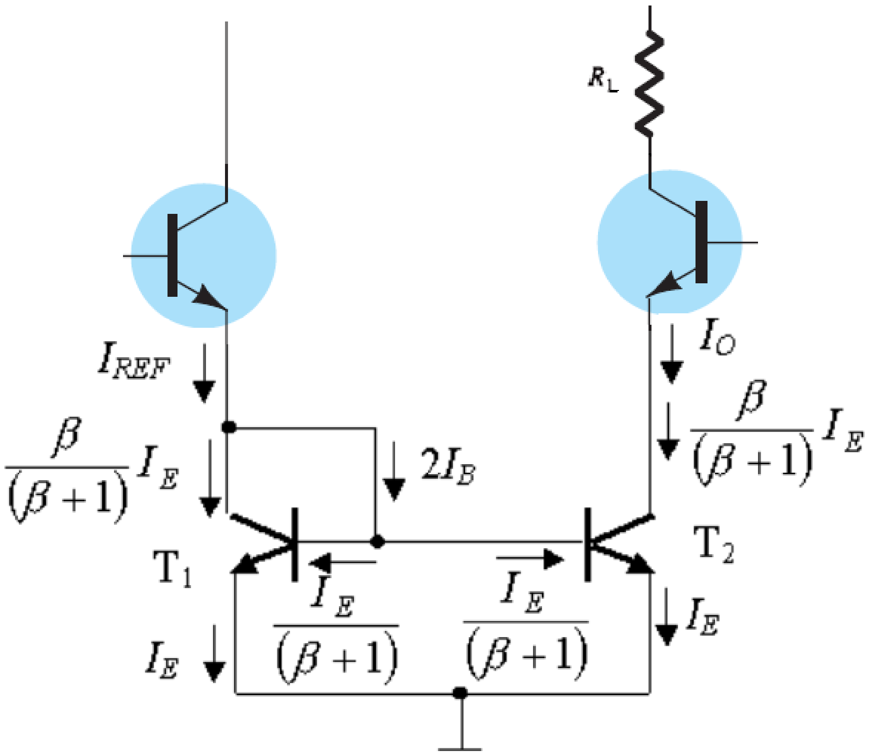


$$V_B = -\frac{R_2}{R_1 + R_2} V_{EE}$$

$$I_E = \frac{V_{EE} - V_E}{R_E} \qquad V_E = V_B - 0.7$$

Constant I_E

Increasing R_E – Current Mirror



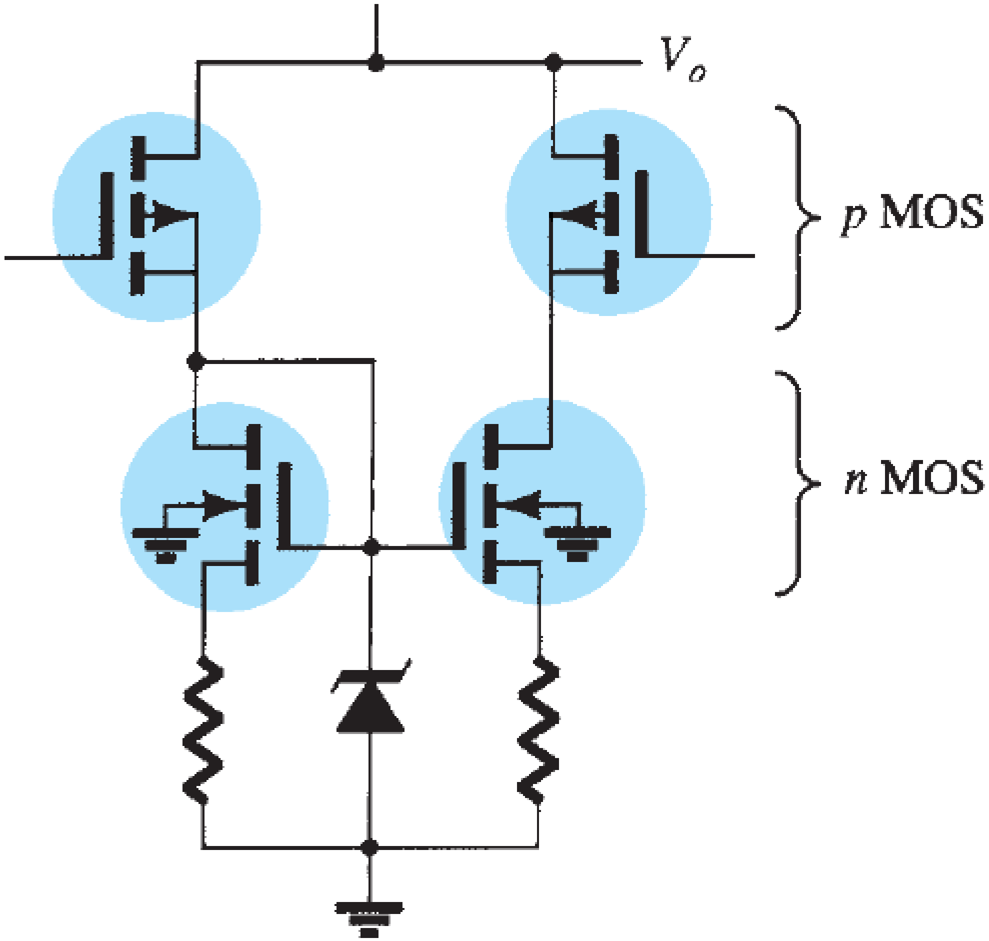
T_1 and T_2 form a current mirror

$$I_{REF} = \frac{\beta}{\beta+1} I_E + 2\frac{I_E}{\beta+1} = \frac{\beta+2}{\beta+1} I_E$$

$$I_O = \frac{\beta}{\beta+1} I_E$$

$$I_O = \frac{1}{1+2/\beta} I_{REF} \cong I_{REF}$$

Using MOS Transistors



Op-Amp Gain

Op-Amps can be connected in *open-loop* or *closed-loop* configurations.

Open-loop: A configuration with no feedback from the op-amp output back to its input. Op-amp open-loop gain typically exceeds 10,000.

Closed-loop: A configuration that has a negative feedback path from the op-amp output back to its input. **Negative feedback** reduces the gain and improves many characteristics of the op-amp.

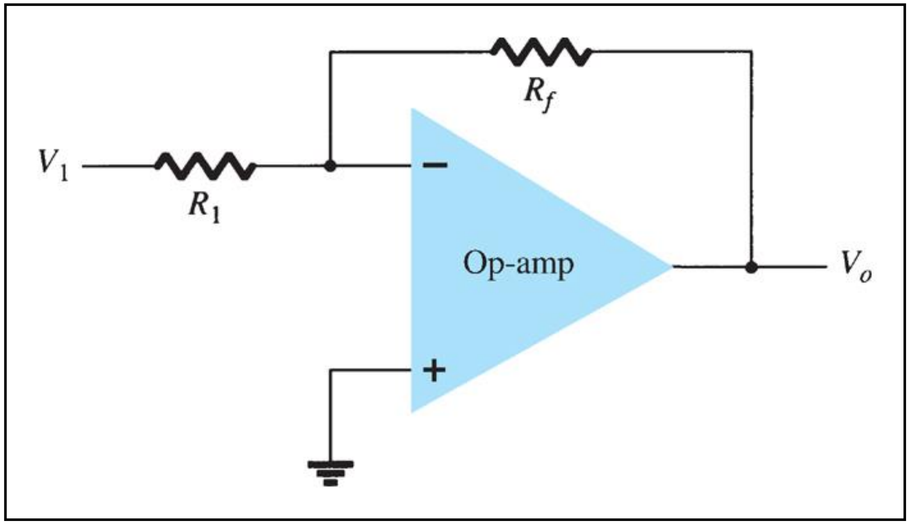
- Closed-loop gain is always lower than open-loop gain.

Inverting Op-Amp

The input signal is applied to the **inverting (–) input**

The **non-inverting input (+)** is grounded

The **feedback resistor** (R_f) is connected from the output to the negative (inverting) input; providing *negative feedback*.



Inverting Op-Amp Gain

Gain is set using external resistors: R_f and R_1

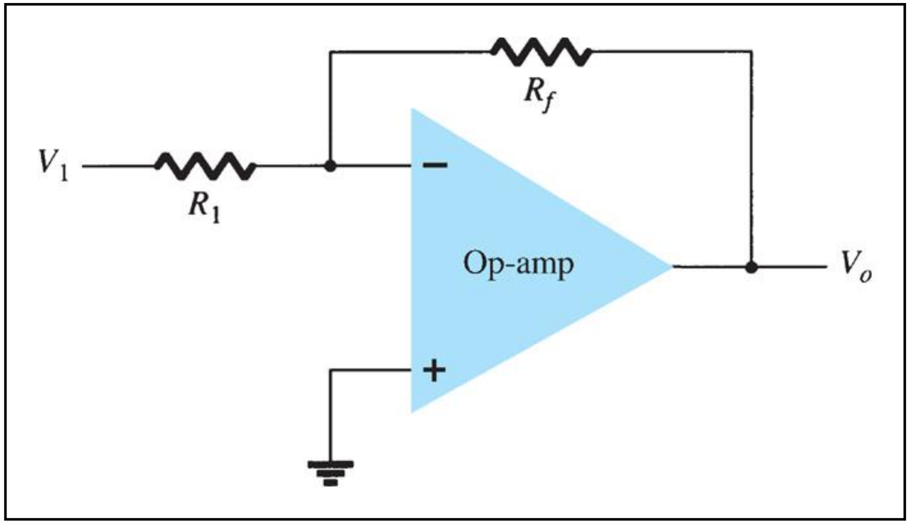
$$A_v = \frac{V_o}{V_i} = \frac{R_f}{R_1}$$

Gain can be set to any value by manipulating the values of R_f and R_1.

Unity gain (A_v = 1):

$$R_f = R_1$$

$$A_v = \frac{-R_f}{R_1} = -1$$

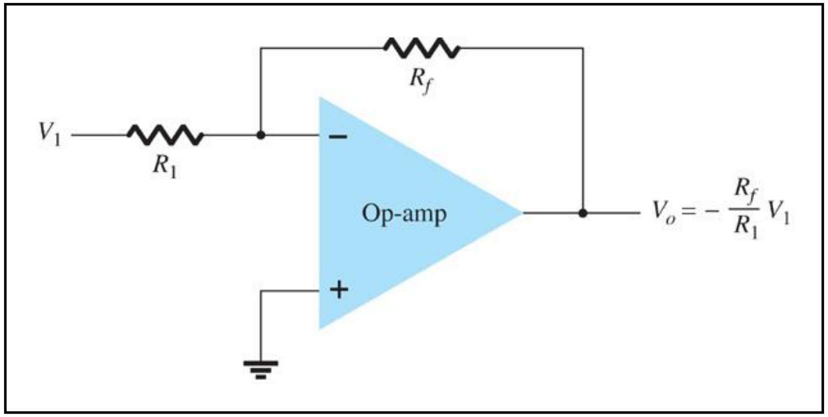


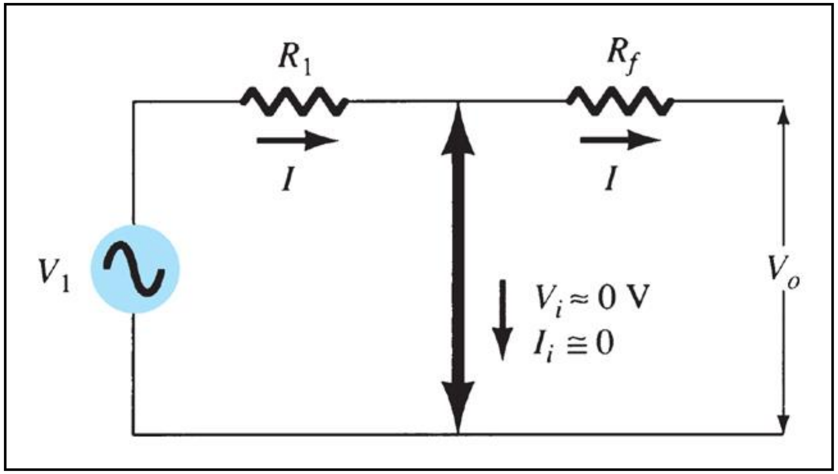
The negative sign denotes a 180° phase shift between input and output.

Virtual Ground

Virtual ground: A term used to describe the condition where $V_i \cong 0$ V (at the inverting input) when the noninverting input is grounded.

The op-amp has such high input impedance that even with a high gain there is no current through the inverting input pin, therefore all of the input current passes through R_f.





Common Op-Amp Circuits

Inverting amplifier

Noninverting amplifier

Unity follower

Summing amplifier

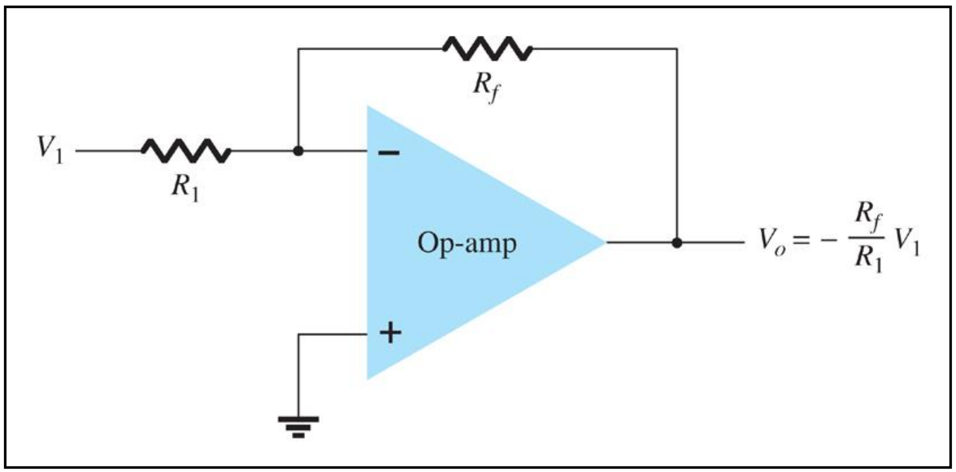
Integrator

Differentiator

Inverting/Noninverting Amplifiers

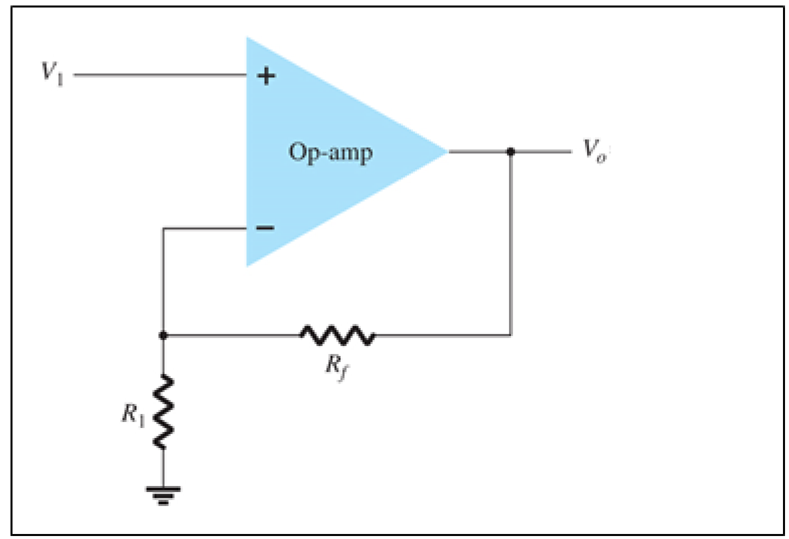
Inverting Amplifier

$$V_o = \frac{-R_f}{R_1} V_1$$

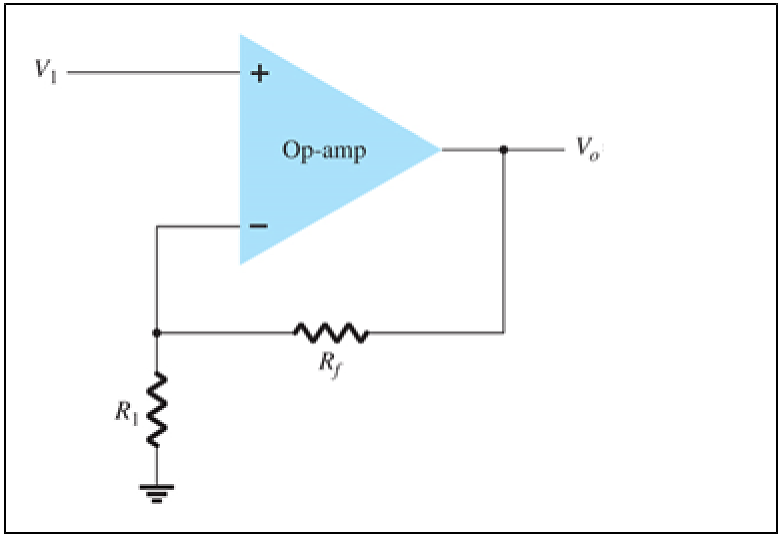


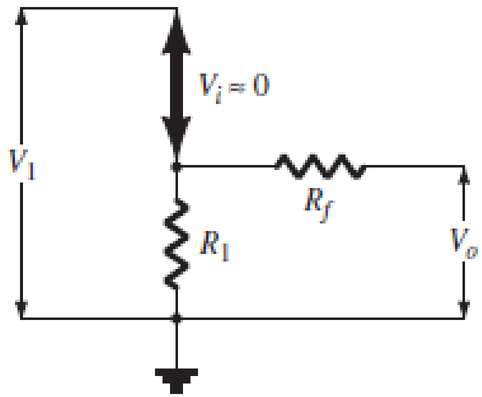
Noninverting Amplifier

$$V_o = ?$$



Noninverting Amplifiers





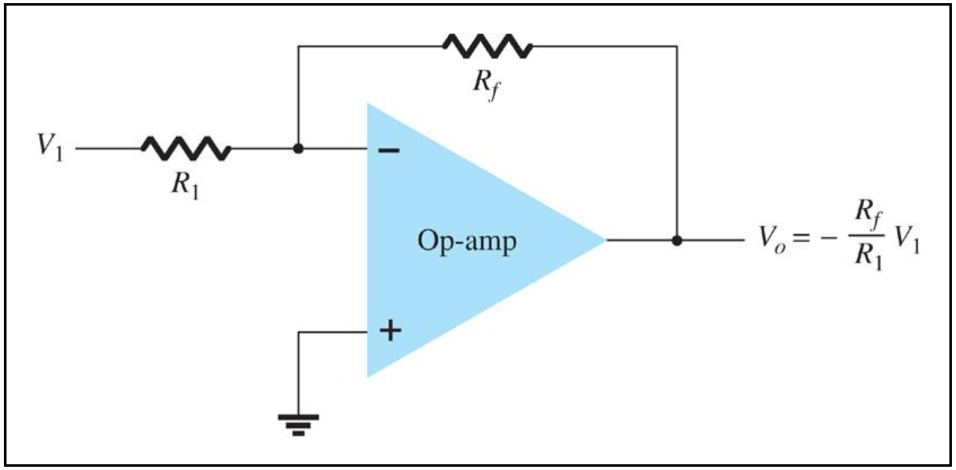
$$V_1 = \frac{R_1}{R_1 + R_f} V_o$$

$$\frac{V_o}{V_1} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1}$$

Noninverting Amplifiers

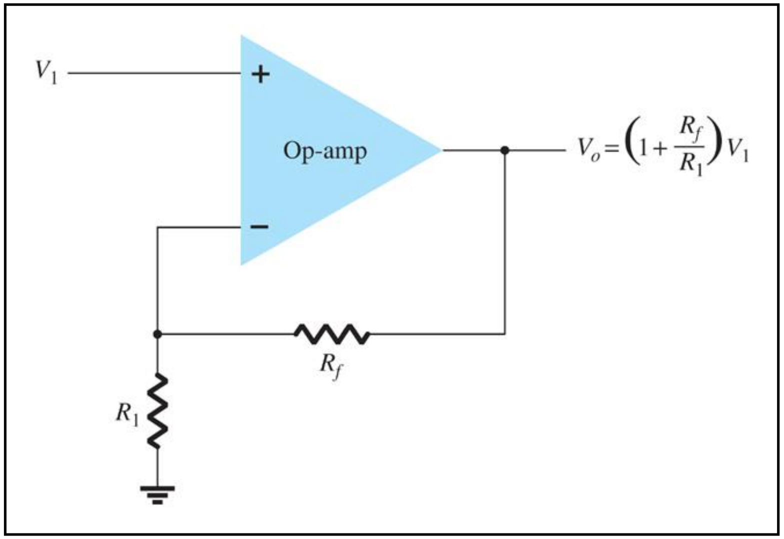
Inverting Amplifier

$$V_o = \frac{-R_f}{R_1} V_1$$

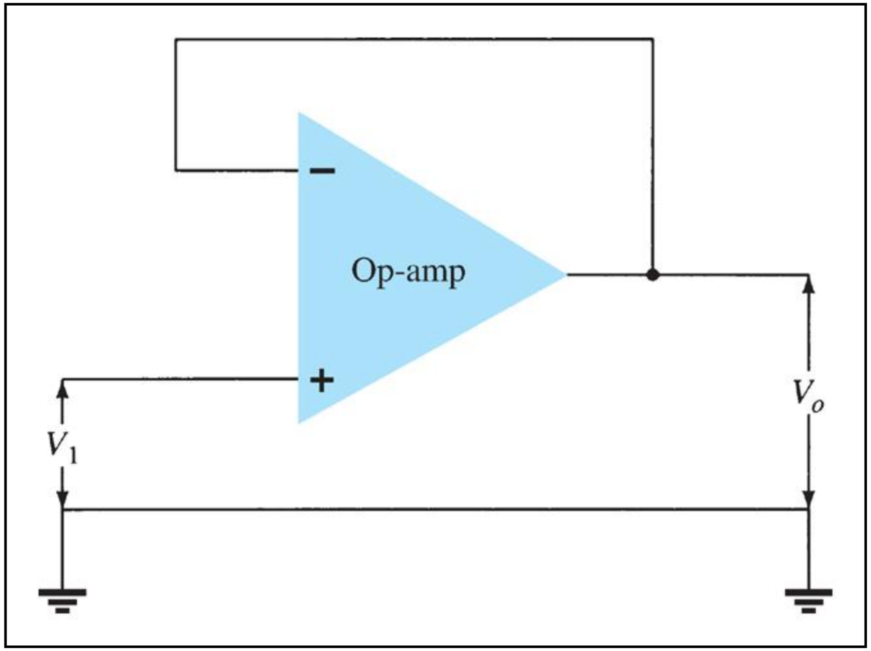


Noninverting Amplifier

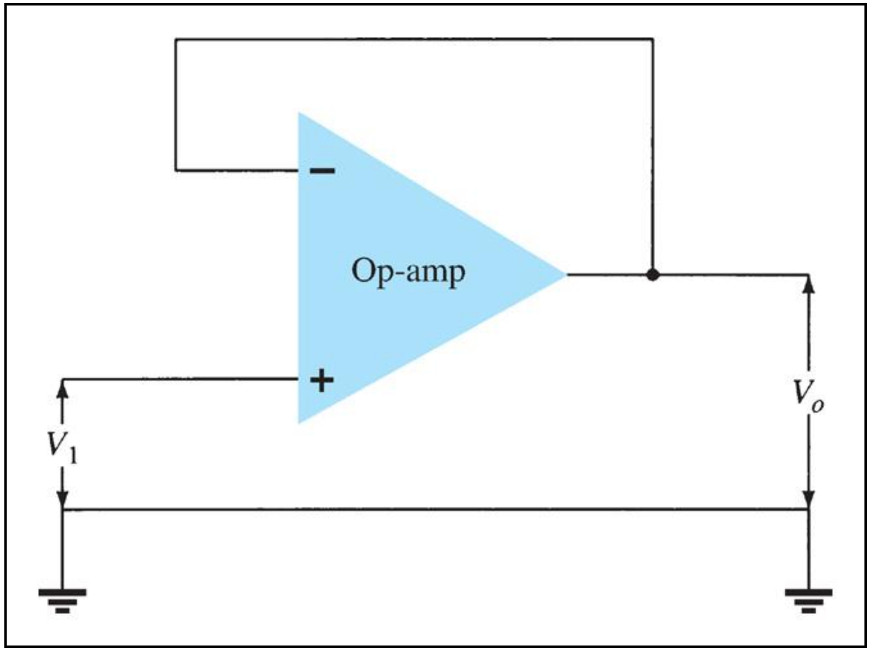
$$V_o = (1 + \frac{R_f}{R_1}) V_1$$

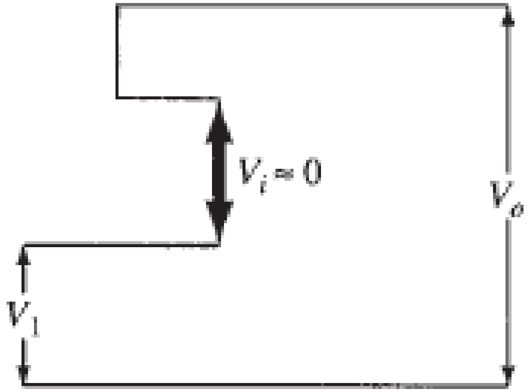


Unity Follower

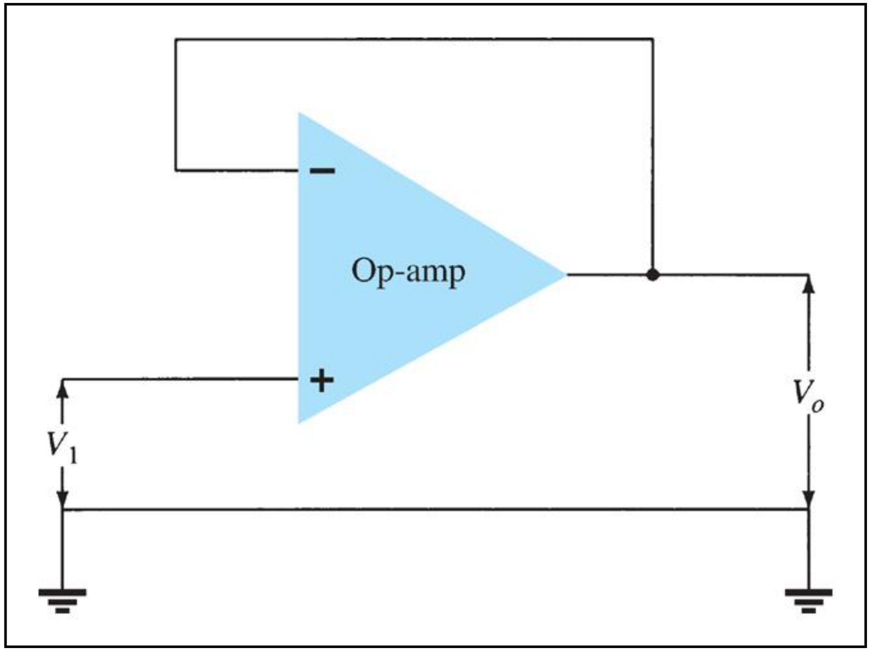


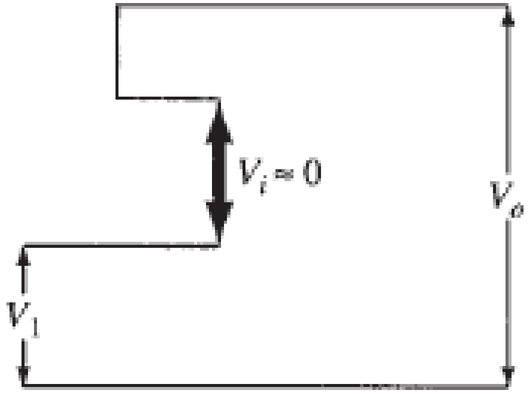
Unity Follower





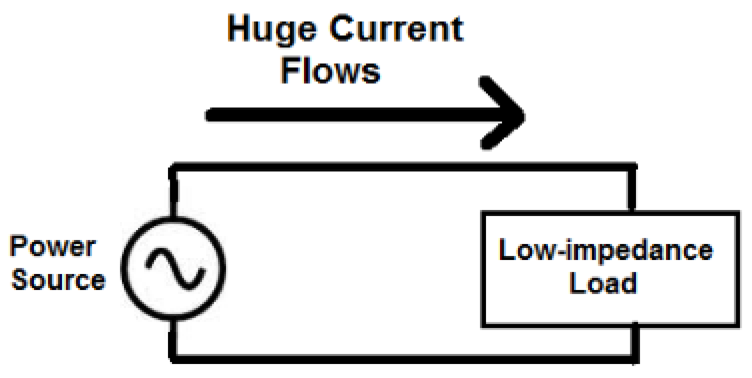
Unity Follower

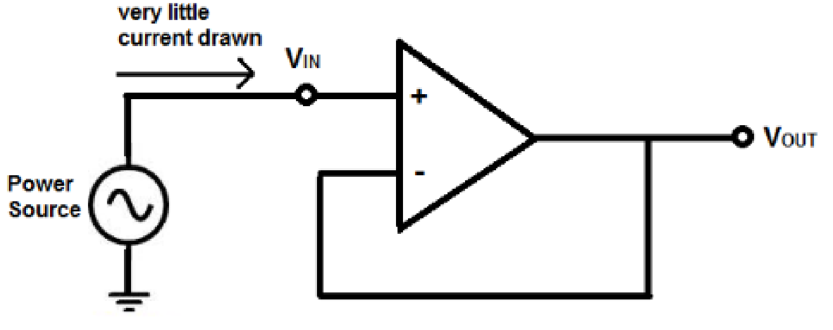




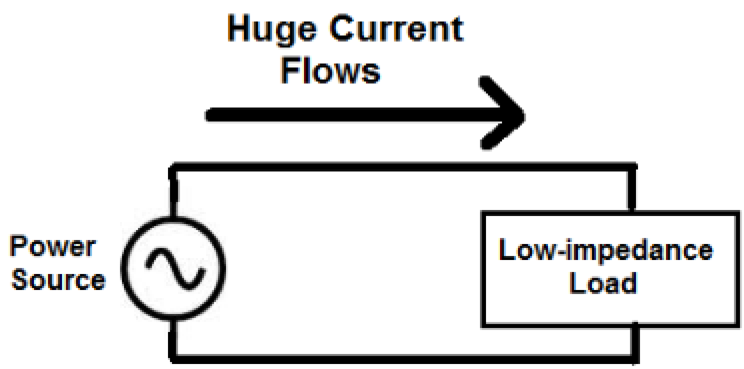
$$V_o = V_1$$

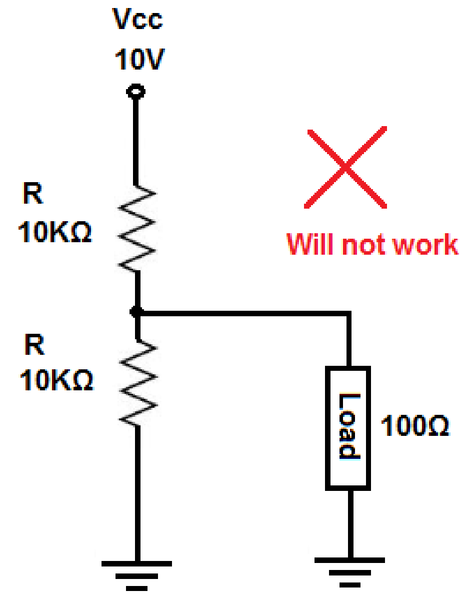
Unity Follower

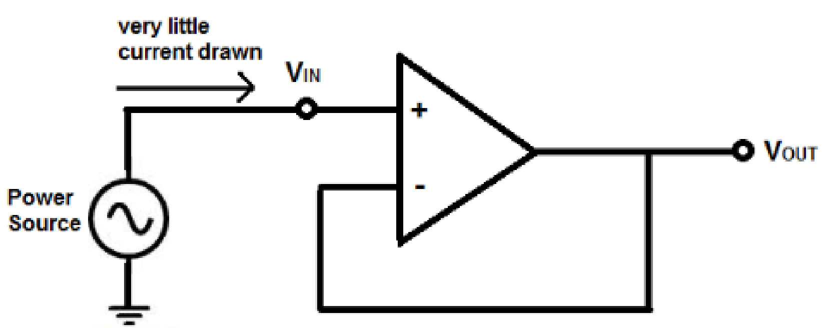


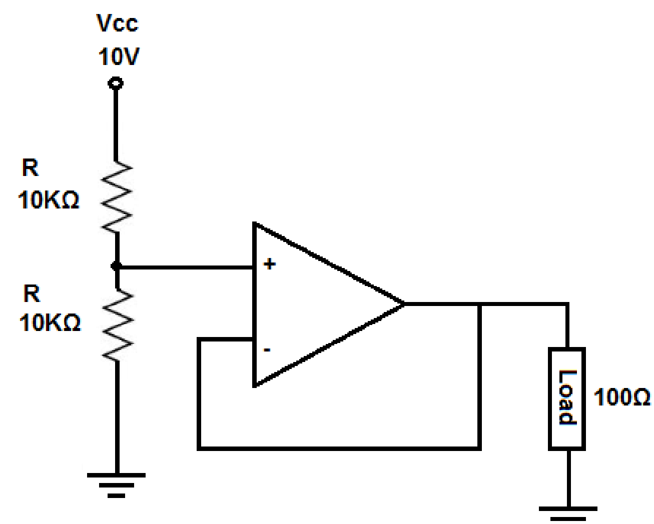


Unity Follower

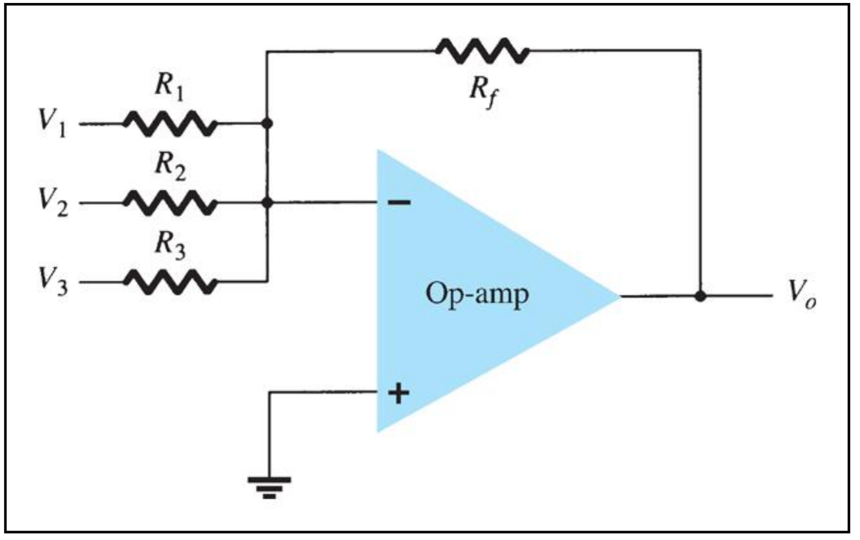




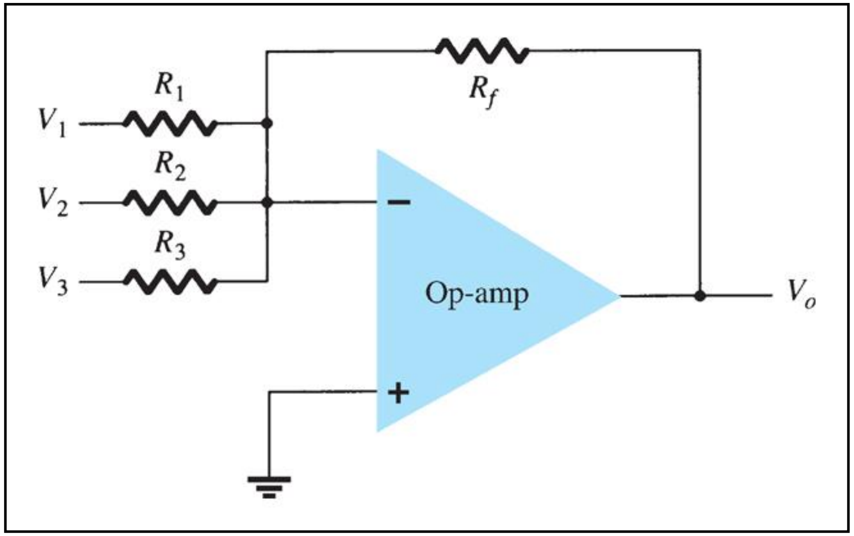


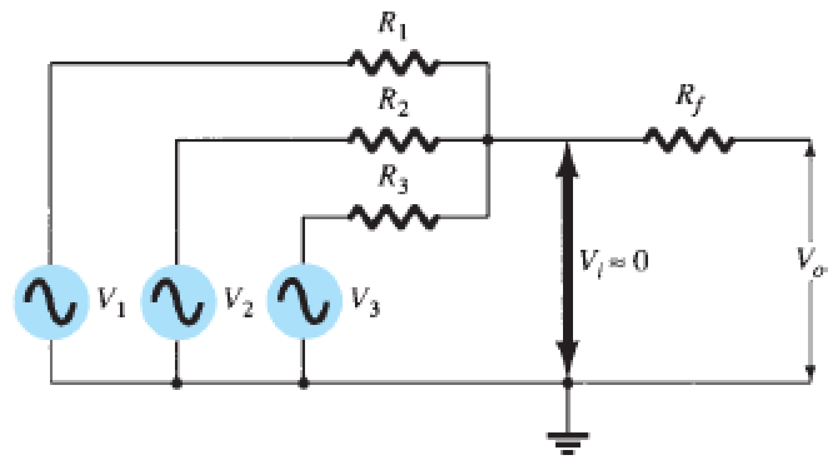


Summing Amplifier

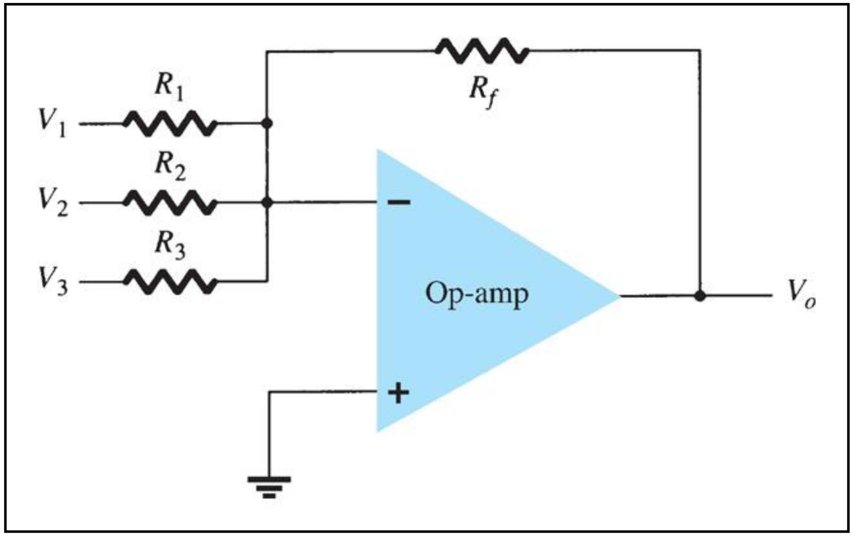


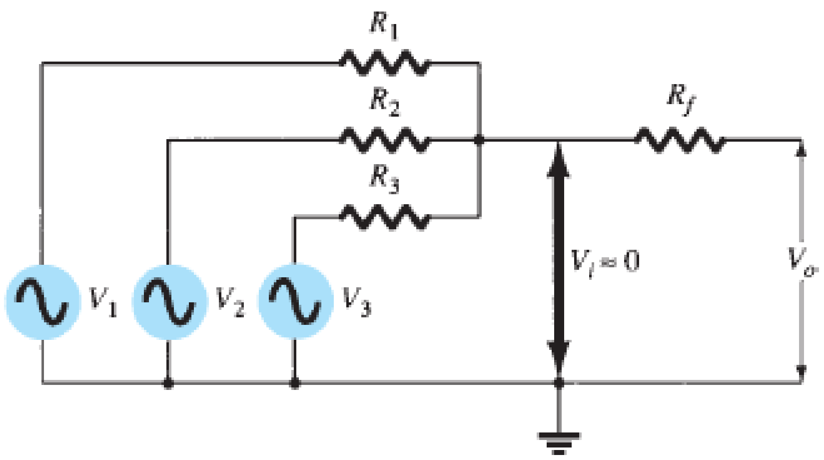
Summing Amplifier





Summing Amplifier

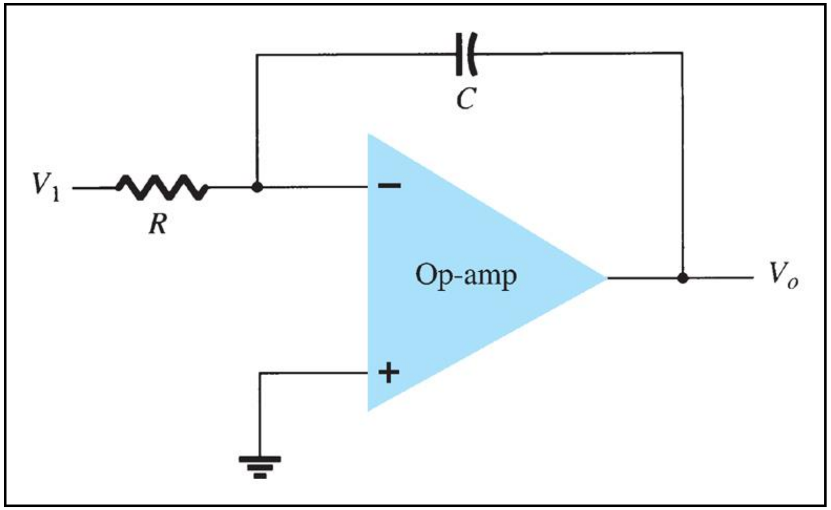


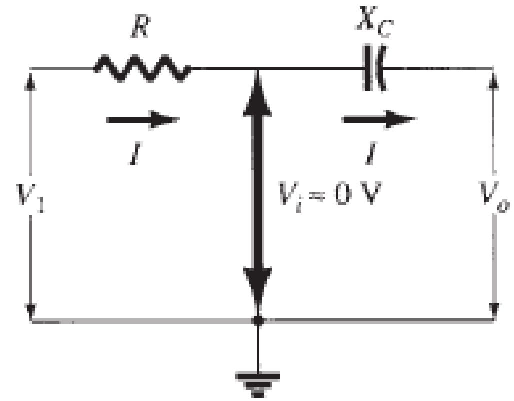


Because the op-amp has a high input impedance, the multiple inputs are treated as separate inputs.

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

Integrator

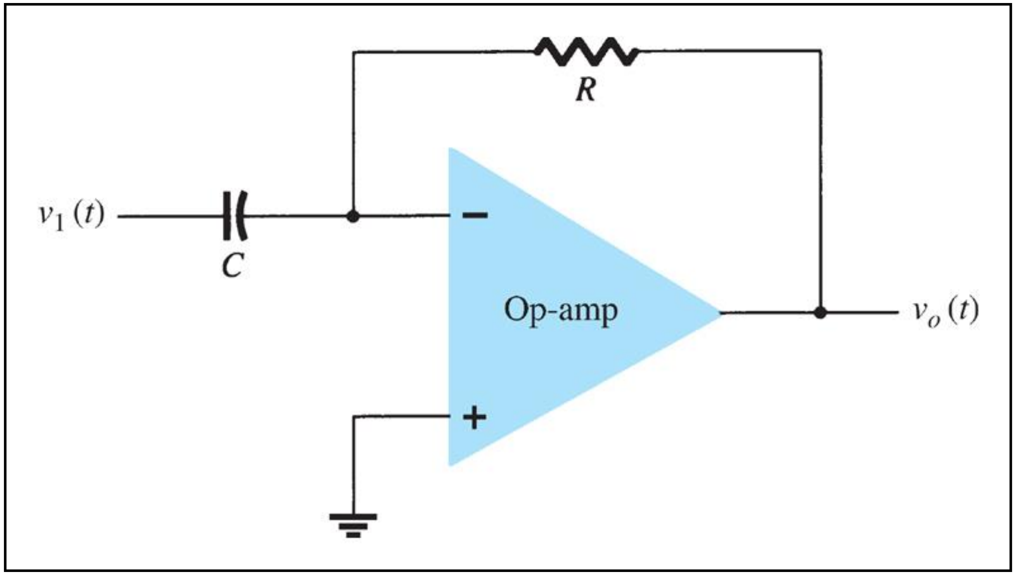




$$v_o(t) = -\frac{1}{RC}\int v_1(t)dt$$

The output is the integral of the input; i.e., proportional to the area under the input waveform. This circuit is useful in low-pass filter circuits and sensor conditioning circuits.

Differentiator



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

The differentiator takes the derivative of the input. This circuit is useful in high-pass filter circuits.