INTEGRATED TECHNICAL EDUCATION CLUSTER
AT ALAMEERIA

J-601-1448
Electronic Principals

Lecture #10
Operational Amplifiers

Instructor:
Dr. Ahmad El-Banna

December 2014

Agenda

- Introduction
- Differential Amplifier Circuit
- Practical Op-Amp Circuits & Applications

Single-Ended Input & Double-Ended (Differential) Input

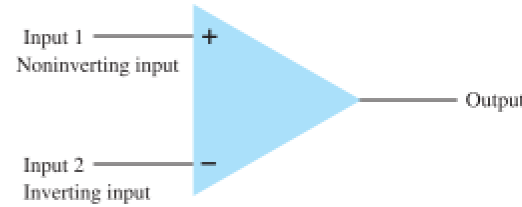


FIG. 10.1
Basic op-amp.

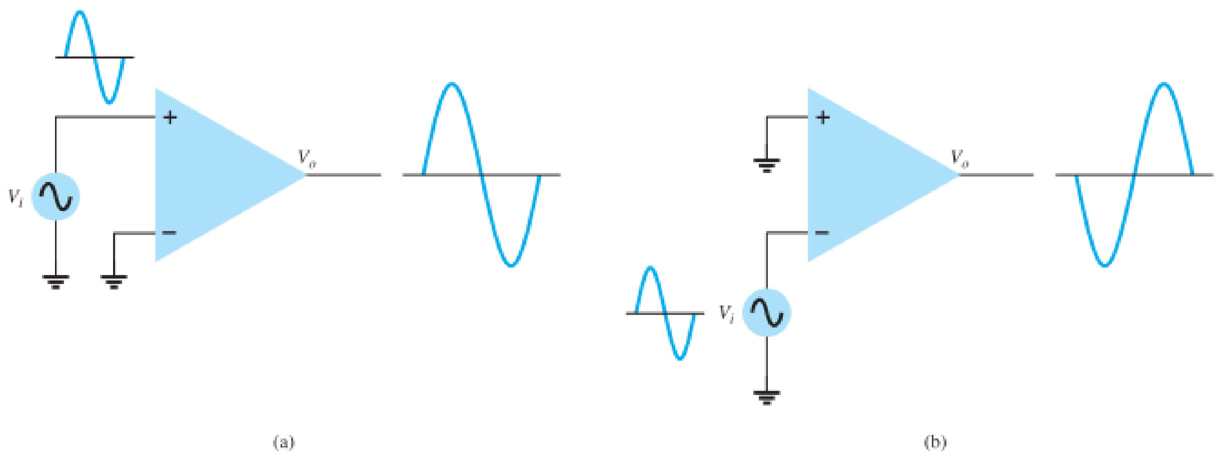


FIG. 10.2
Single-ended operation.

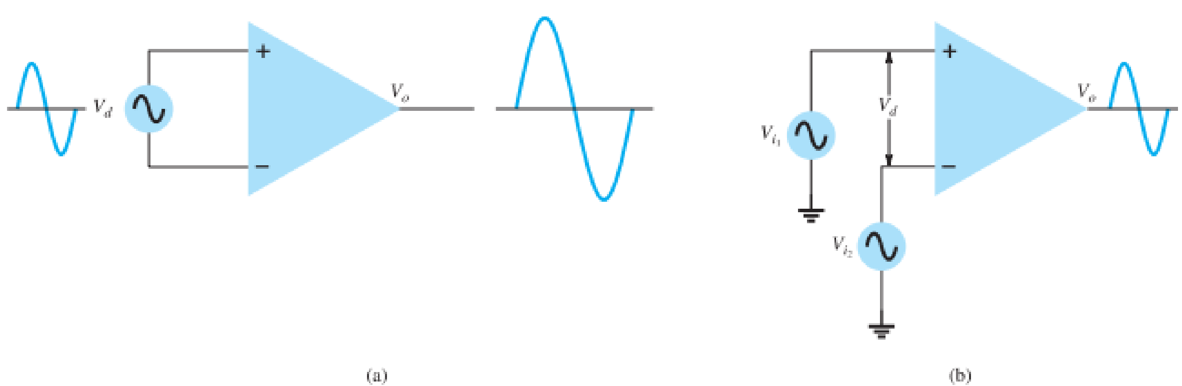


FIG. 10.3
Double-ended (differential) operation.

Double-ended output and Common Mode Operation

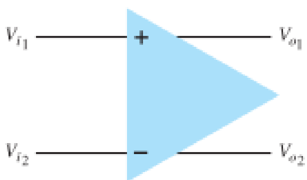


FIG. 10.4
Double-ended input with double-ended output.

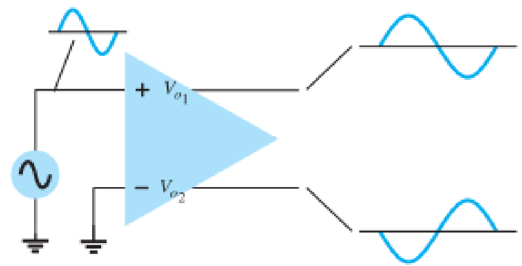


FIG. 10.5
Single-ended input with double-ended output.

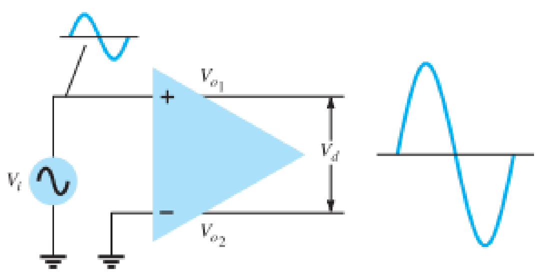


FIG. 10.6
Differential-output.

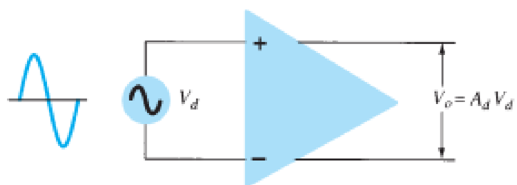


FIG. 10.7
Differential-input, differential-output operation.

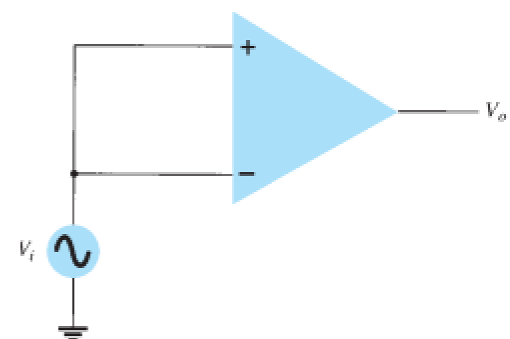


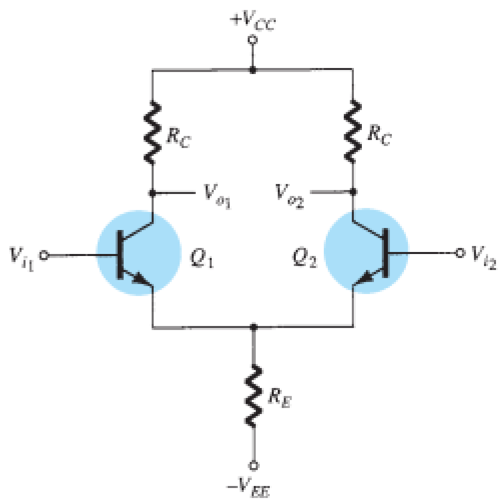
FIG. 10.8
Common-mode operation.

Differential Amplifier Circuit

If an input signal is applied to either input with the other input connected to ground, the operation is referred to as "single-ended."

If two opposite-polarity input signals are applied, the operation is referred to as "double-ended."

If the same input is applied to both inputs, the operation is called "common-mode."



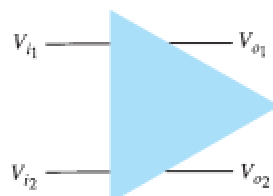
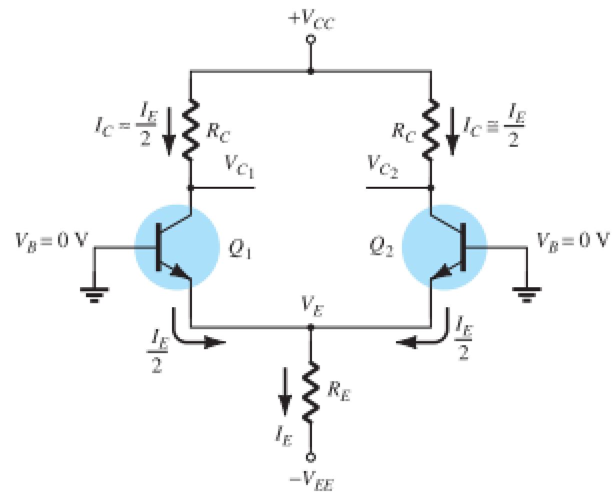


FIG. 10.9
Basic differential amplifier circuit.



DC Bias

$$V_E = 0\text{ V} - V_{BE} = -0.7\text{ V}$$

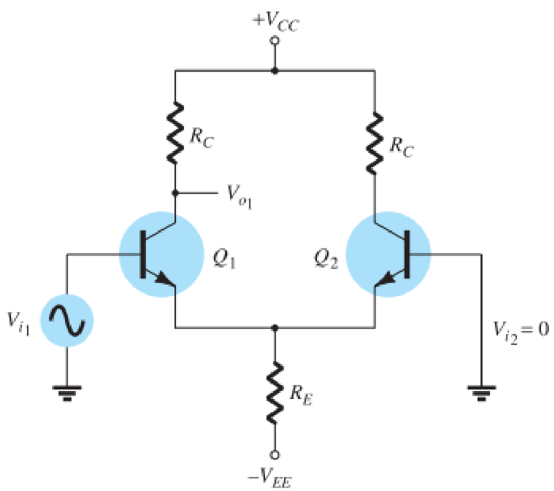
$$I_E = \frac{V_E - (-V_{EE})}{R_E} \approx \frac{V_{EE} - 0.7\text{ V}}{R_E}$$

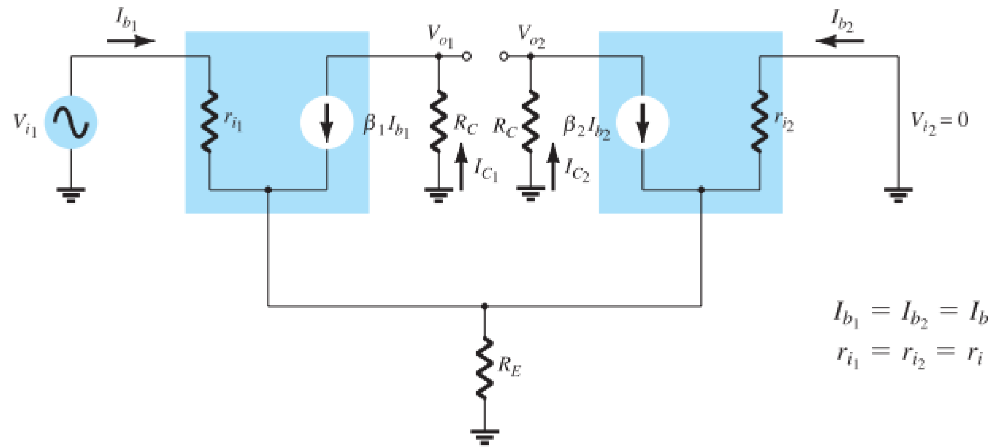
$$I_{C_1} = I_{C_2} = \frac{I_E}{2}$$

$$V_{C_1} = V_{C_2} = V_{CC} - I_C R_C = V_{CC} - \frac{I_E}{2} R_C$$

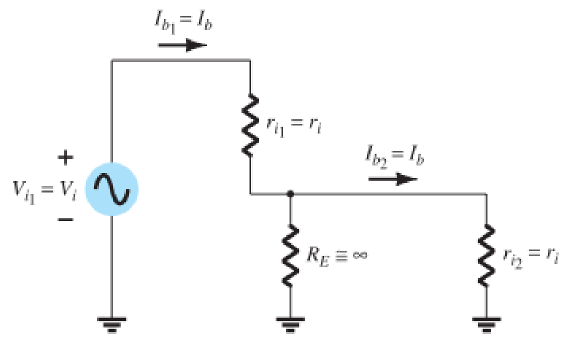
AC Operation

Single-Ended AC Voltage Gain





$$I_{b_1} = I_{b_2} = I_b$$
$$r_{i_1} = r_{i_2} = r_i = \beta r_e$$



$$V_{i_1} - I_b r_i - I_b r_i = 0$$

$$I_b = \frac{V_{i_1}}{2r_i} = \frac{V_i}{2\beta r_e}$$

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

$$I_C = \beta I_b = \beta \frac{V_i}{2\beta r_e} = \frac{V_i}{2r_e}$$

$$V_o = I_C R_C = \frac{V_i}{2r_e} R_C = \frac{R_C}{2r_e} V_i$$

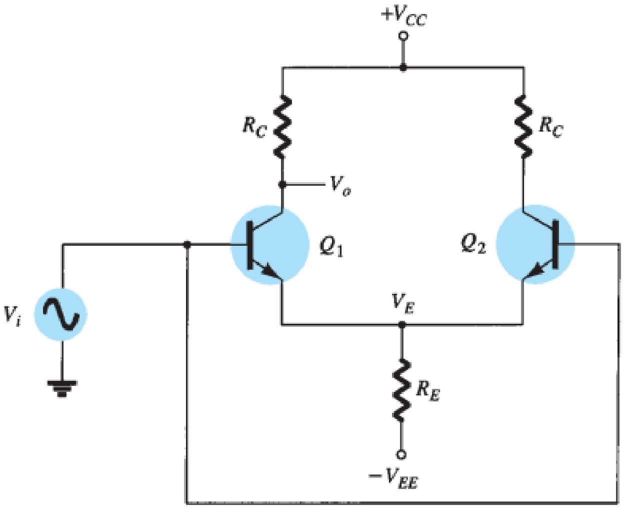
$$A_v = \frac{V_o}{V_i} = \frac{R_C}{2r_e}$$

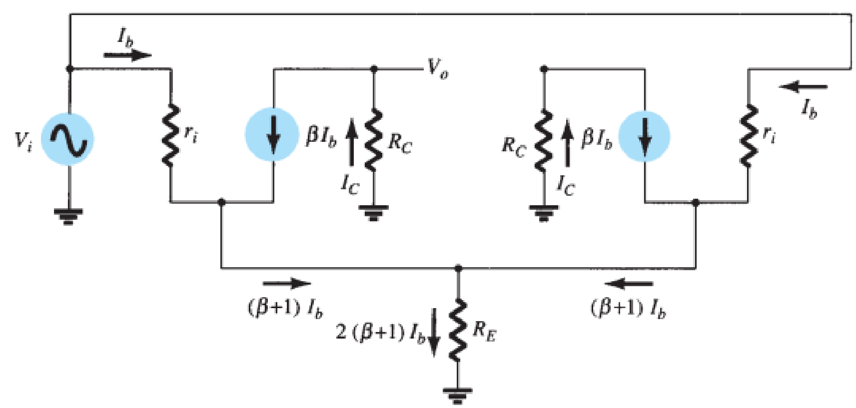
Double-Ended AC Voltage Gain

$$A_d = \frac{V_o}{V_d} = \frac{R_C}{r_e}$$

where $V_d = V_{i_1} - V_{i_2}$.

Common Mode Operation





$$I_b = \frac{V_i - 2(\beta + 1)I_b R_E}{r_i}$$

which can be rewritten as

$$I_b = \frac{V_i}{r_i + 2(\beta + 1)R_E}$$

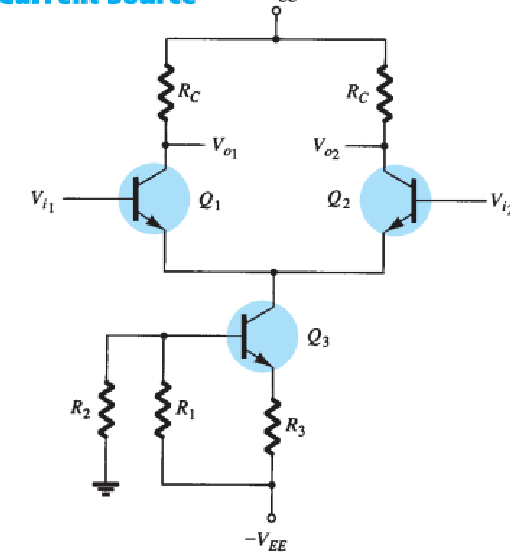
The output voltage magnitude is then

$$V_o = I_C R_C = \beta I_b R_C = \frac{\beta V_i R_C}{r_i + 2(\beta + 1)R_E}$$

providing a voltage gain magnitude of

$$A_c = \frac{V_o}{V_i} = \frac{\beta R_C}{r_i + 2(\beta + 1)R_E}$$

Use of Constant-Current Source



Op-Amp Equivalent Circuit

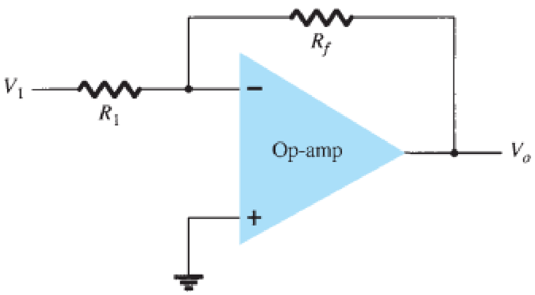


FIG. 10.31
Basic op-amp connection.

OP-AMP

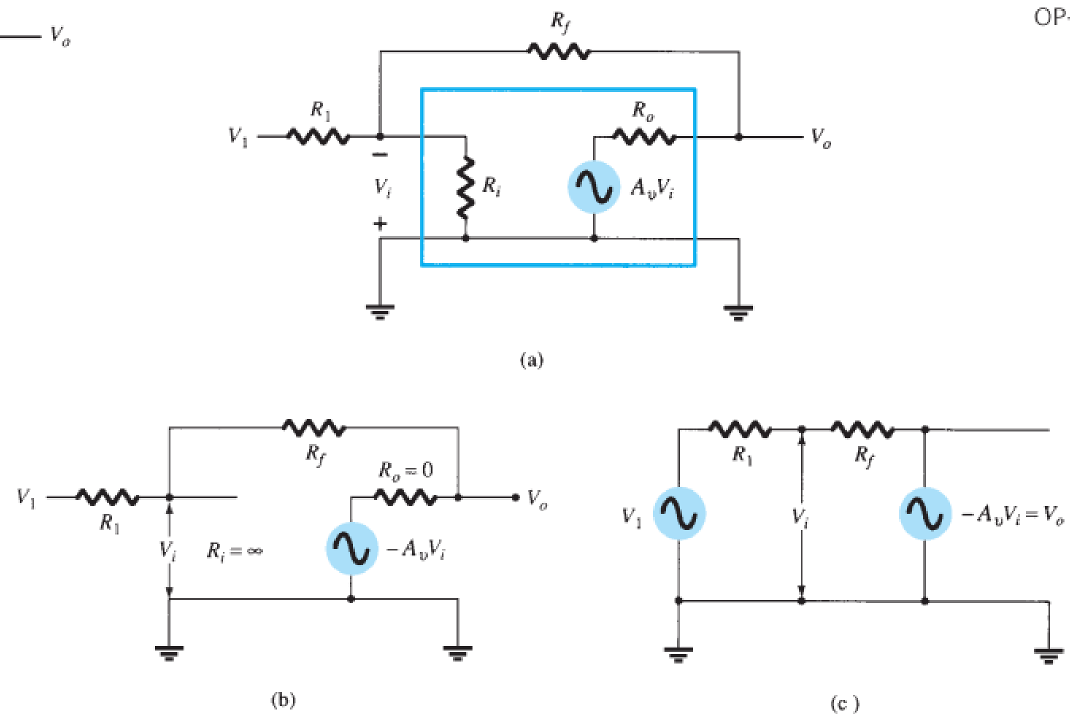


FIG. 10.32
Operation of op-amp as constant-gain multiplier: (a) op-amp ac equivalent circuit; (b) ideal op-amp equivalent circuit; (c) redrawn equivalent circuit.

Inverting & Non-Inverting Amplifier

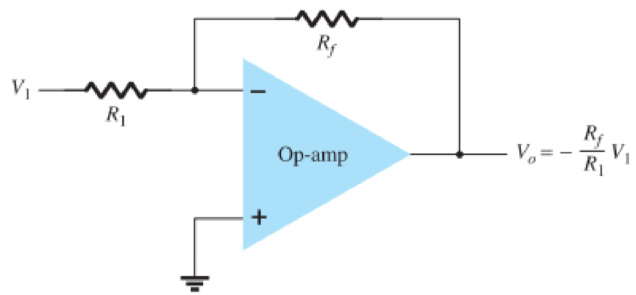


FIG. 10.34
Inverting constant-gain multiplier.

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

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

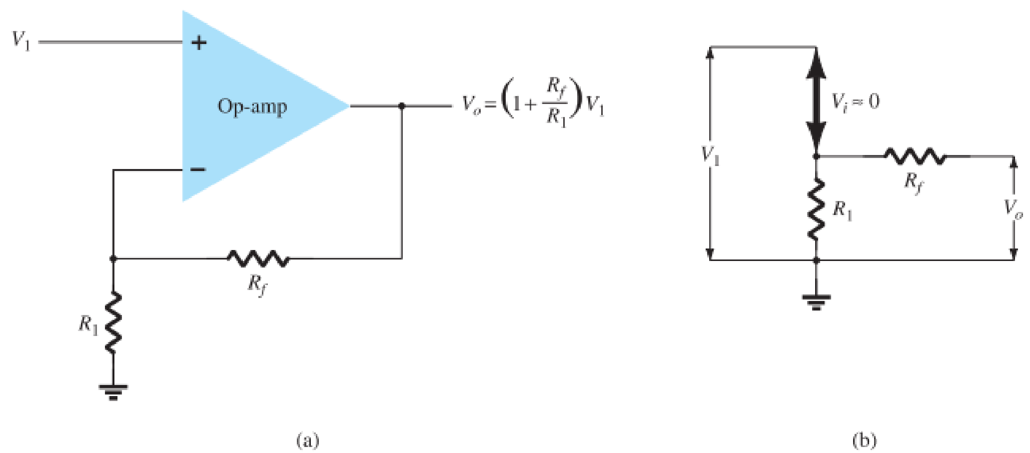


FIG. 10.35
Noninverting constant-gain multiplier.

Unity Follower & Summing Amplifier

$V_o = V_1$

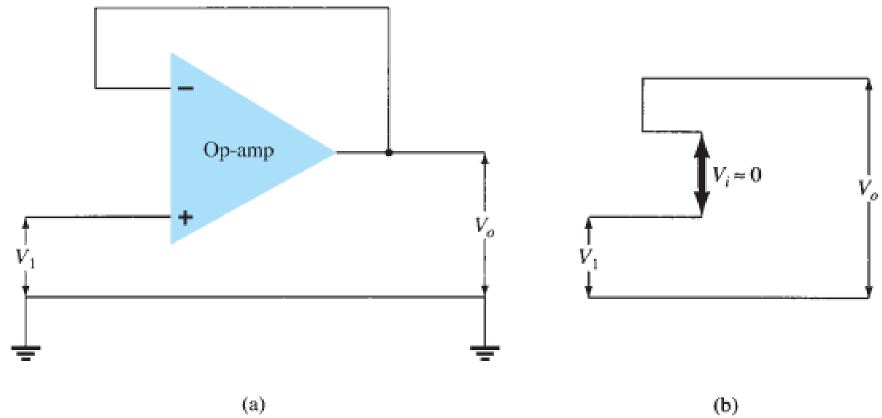


FIG. 10.36

(a) Unity follower; (b) virtual-ground equivalent circuit.

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

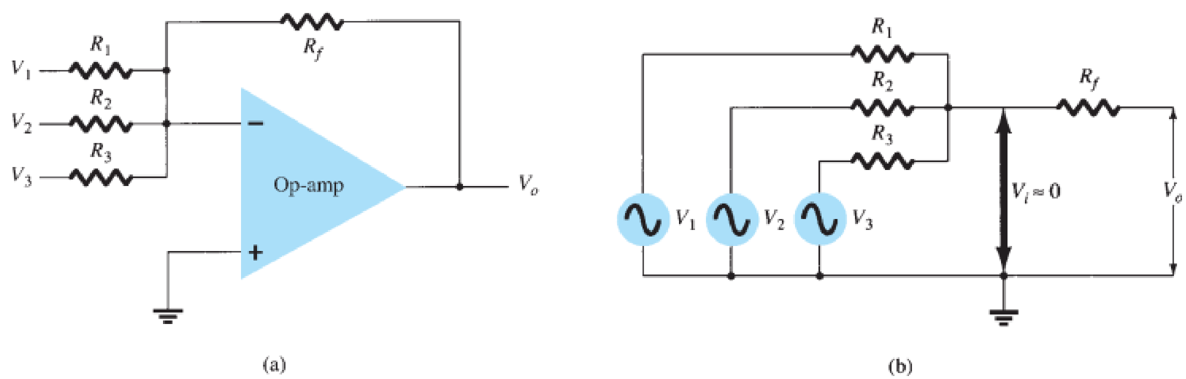


FIG. 10.37

(a) Summing amplifier; (b) virtual-ground equivalent circuit.

Integrator & Differentiator

$$X_C = \frac{1}{j\omega C} = \frac{1}{sC}$$

$$I = \frac{V_1}{R} = -\frac{V_o}{X_C} = \frac{-V_o}{1/sC} = -sCV_o$$

$$\frac{V_o}{V_1} = \frac{-1}{sCR}$$

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

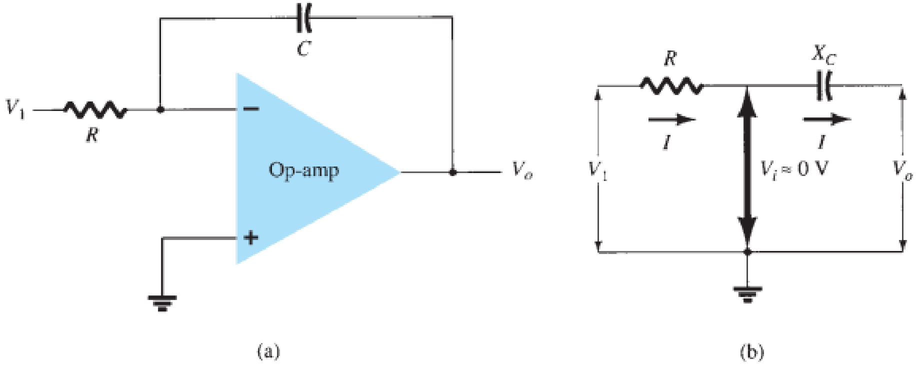


FIG. 10.38
Integrator.

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

where the scale factor is $-RC$.

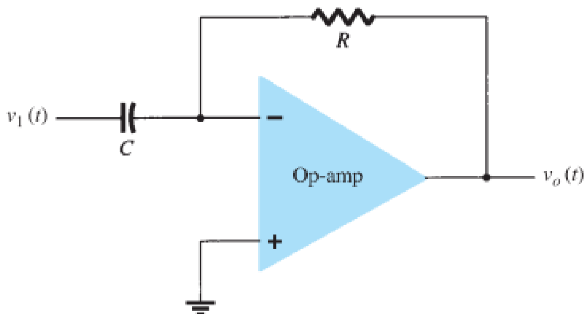


FIG. 10.41
Differentiator circuit.

Voltage Subtraction

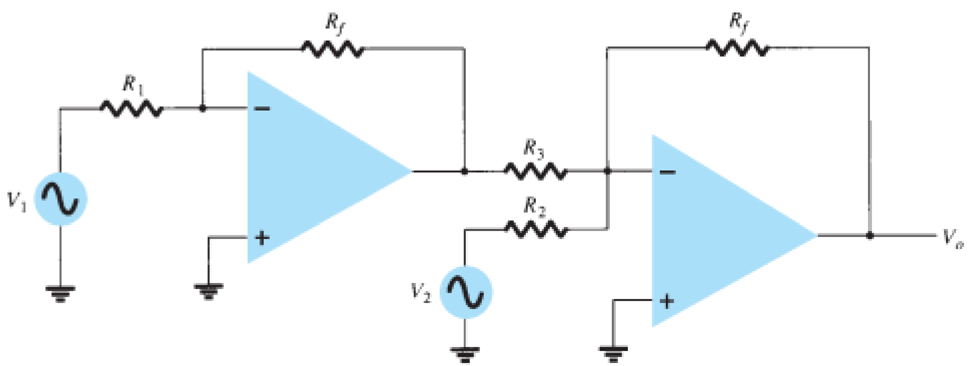


FIG. 11.10
Circuit for subtracting two signals.

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

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

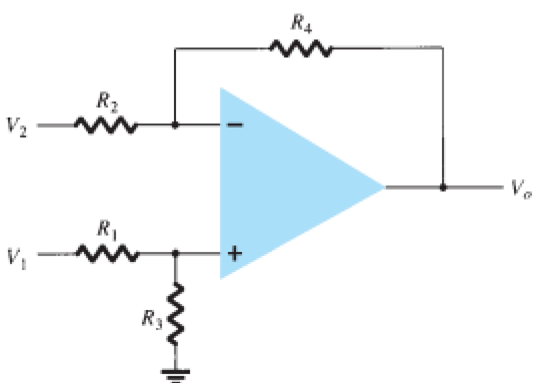


FIG. 11.11
Subtraction circuit.

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

Active Filters

LPF

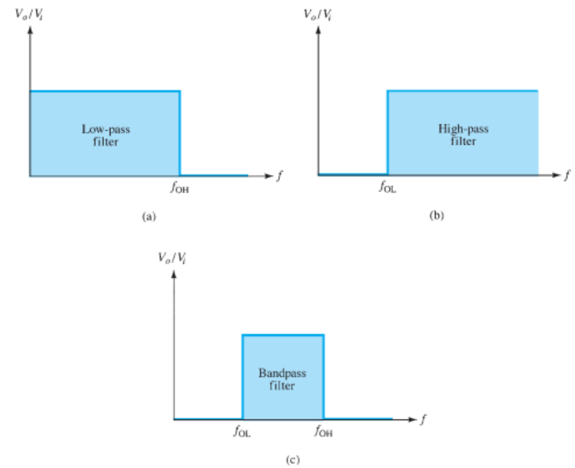
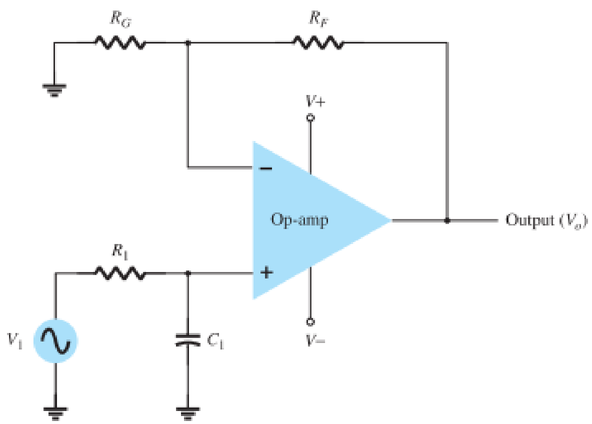
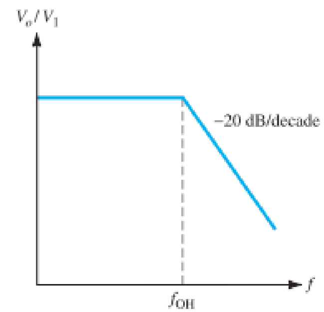


FIG. 11.30
Ideal filter response: (a) low-pass; (b) high-pass; (c) bandpass.





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

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

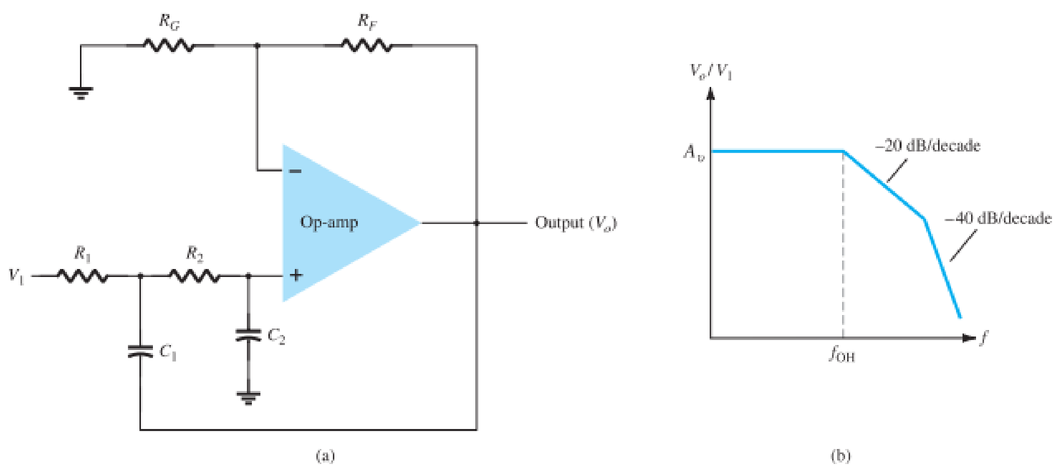
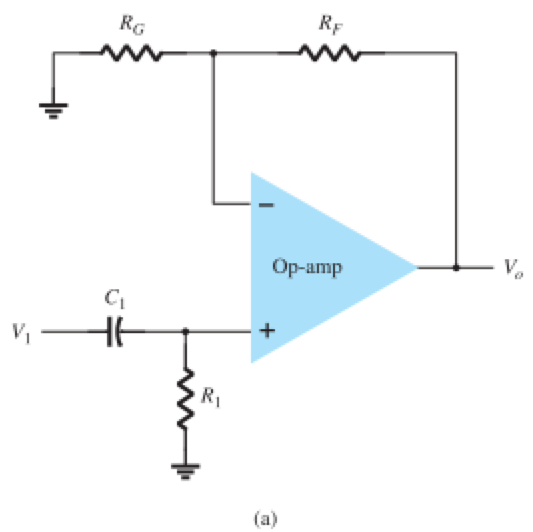
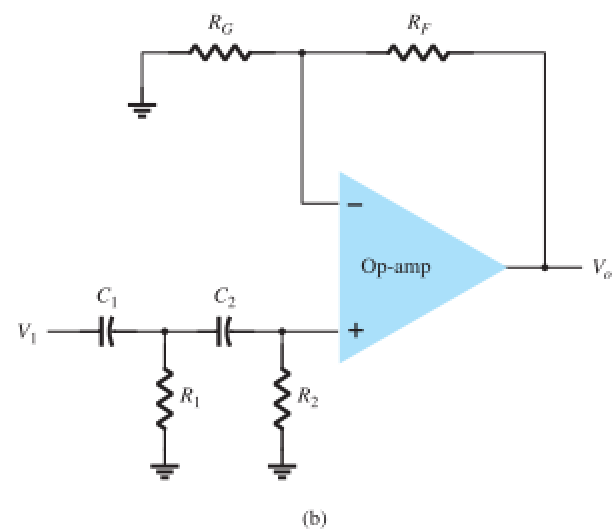


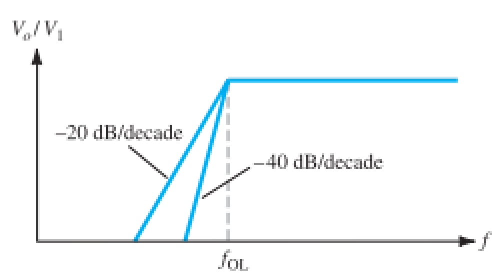
FIG. 11.32
Second-order low-pass active filter.

High Pass Filter

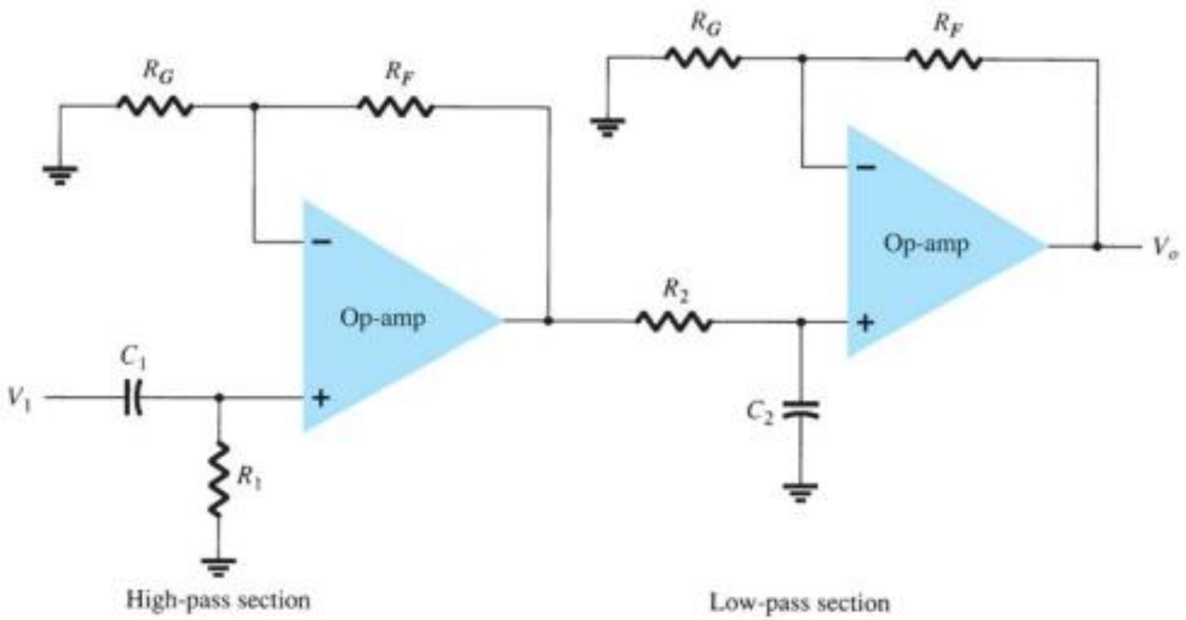
$$f_{OL} = \frac{1}{2\pi R_1 C_1}$$



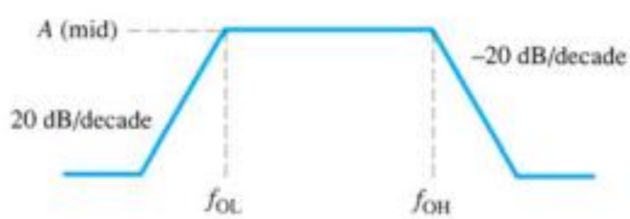




Band Pass Filter



(a)



- For more details, refer to:
  - Chapter 10 & 11, Electronic Devices and Circuits, Boylestad.
- The lecture is available online at:
  - https://speakerdeck.com/ahmad_elbanna
- For inquires, send to:
  - ahmad.elbanna@feng.bu.edu.eg