Chapter 3-Webster

Amplifiers and Signal Processing

Applications of Operational Amplifier In Biological Signals and Systems

The three major operations done on biological signals using Op-Amp:

1) Amplifications and Attenuations
2) DC offsetting: add or subtract a DC
3) Filtering: Shape signal's frequency content

Ideal Op-Amp

Most bioelectric signals are small and require amplifications

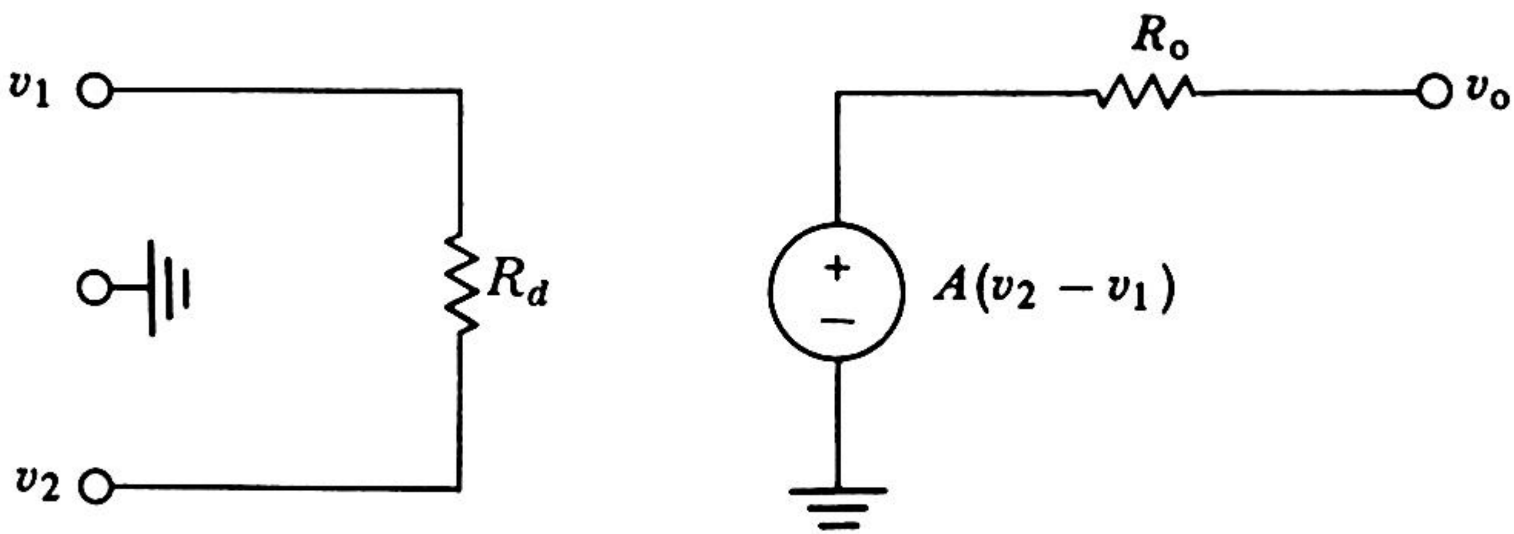
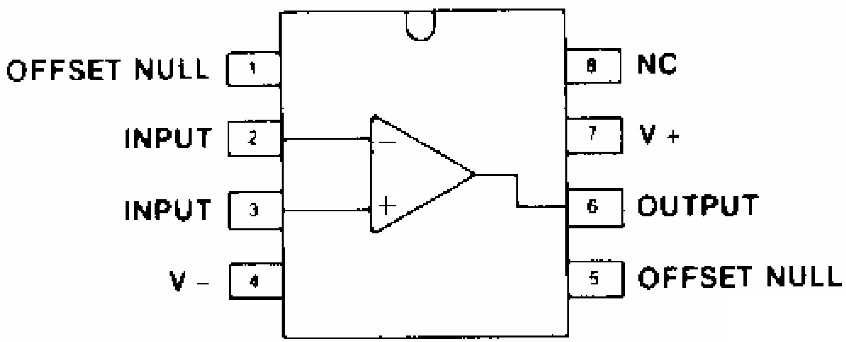


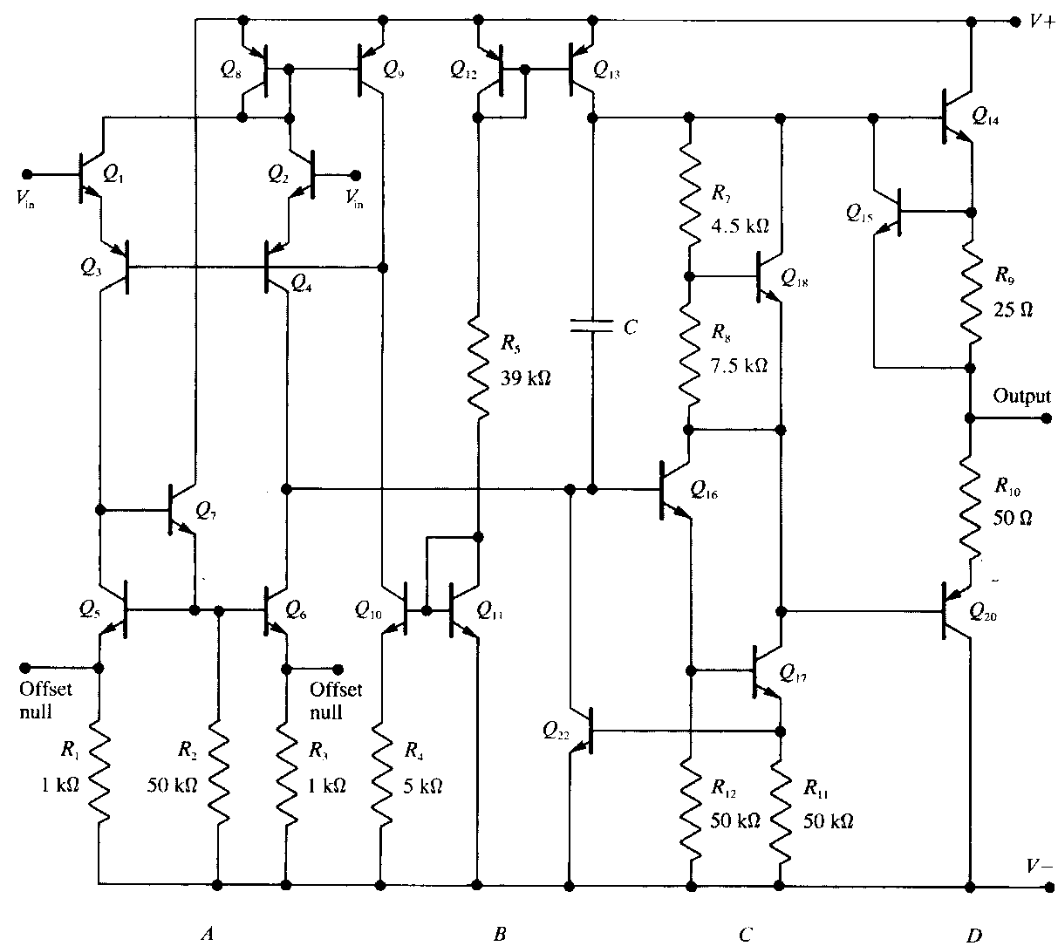
Figure 3.1 Op-amp equivalent circuit. The two inputs are υ_1 and υ_2. A differential voltage between them causes current flow through the differential resistance R_d. The differential voltage is multiplied by A, the gain of the op amp, to generate the output-voltage source. Any current flowing to the output terminal v_o must pass through the output resistance R_o.

Inside the Op-Amp (IC-chip)

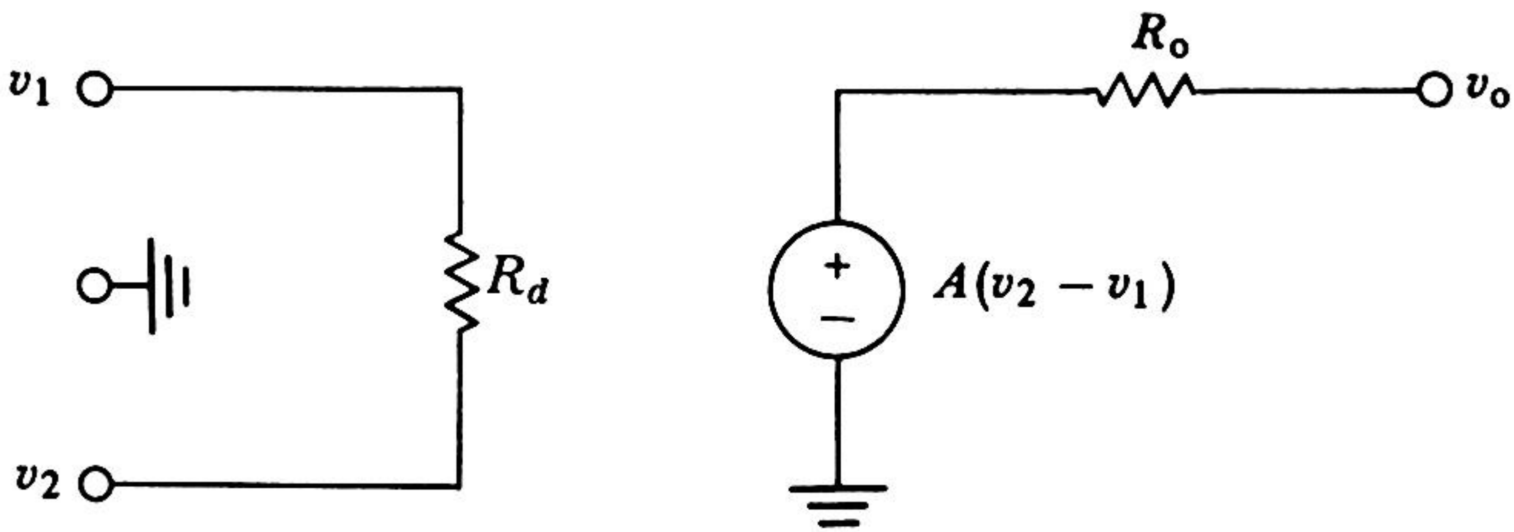


741 op amp

20 transistors
11 resistors
1 capacitor



Ideal Characteristics



1- $A = \infty$ (gain is infinity)

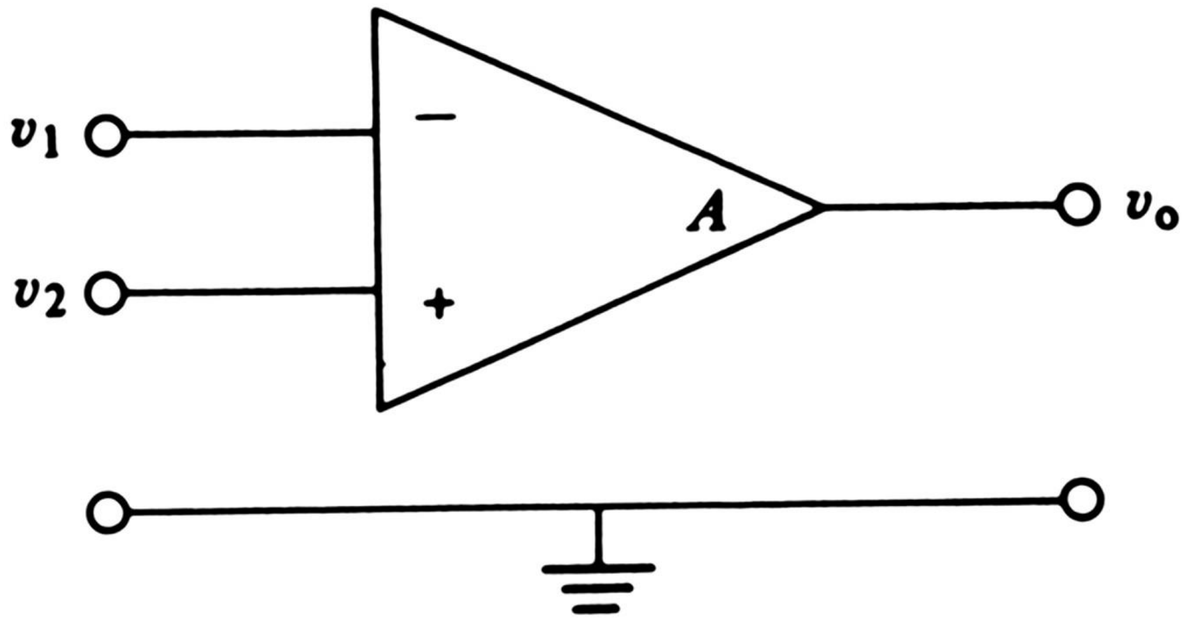
2- $V_o = 0$, when $v_1 = v_2$ (no offset voltage)

3- $R_d = \infty$ (input impedance is infinity)

4- $R_o = 0$ (output impedance is zero)

5- Bandwidth $= \infty$ (no frequency response limitations) and no phase shift

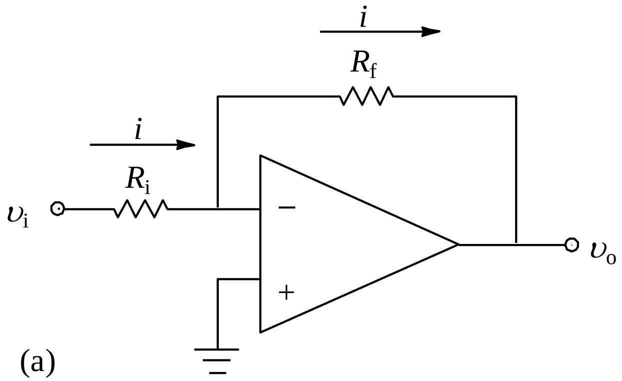
Two Basic Rules

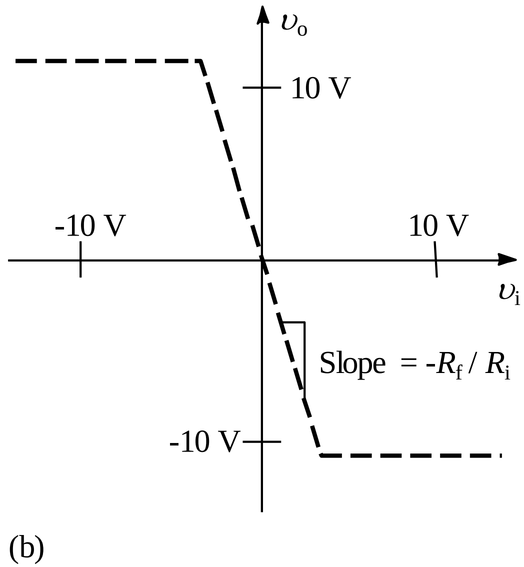


Rule 1
When the op-amp output is in its linear range, the two input terminals are at the same voltage.

Rule 2
No current flows into or out of either input terminal of the op amp.

Inverting Amplifier





$$v_o = -\frac{R_f}{R_i} v_i \qquad G = \frac{v_o}{v_i} = -\frac{R_f}{R_i}$$

Figure 3.3 (a) An inverting amplified. Current flowing through the input resistor R_i also flows through the feedback resistor R_f. (b) The input-output plot shows a slope of $-R_f / R_i$ in the central portion, but the output saturates at about ±13 V.

Example 3.1

The output of a biopotential preamplifier that measures the electro-oculogram is an undesired dc voltage of ±5 V due to electrode half-cell potentials, with a desired signal of ±1 V superimposed. Design a circuit that will balance the dc voltage to zero and provide a gain of -10 for the desired signal without saturating the op amp.

Answer 3.1

(a) shows the design. We assume that the balancing voltage (v_b), available from the 5 kΩ potentiometer is, ±10 V. The undesired voltage at v_i = 5V. For v_o = 0, the current through R_f is zero. Therefore the sum of the currents through R_i and R_b, is zero.

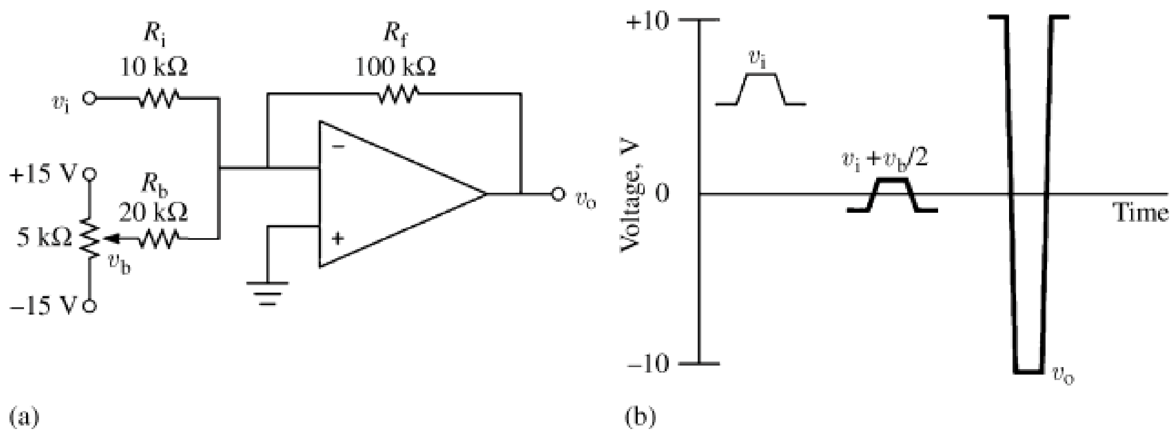


Figure E3.1 (a) This circuit sums the input voltage vi plus one-half of the balancing voltage vb. Thus the output voltage v_o can be set to zero even when vi has a nonzero dc component, (b) The three waveforms show vi, the input voltage; (vi + vb / 2), the balanced-out voltage; and vo, the amplified output voltage. **If v_i were directly amplified, the op amp would saturate.**

$$\frac{v_i}{R_i} + \frac{v_b}{R_b} = 0$$

$$R_b = \frac{-R_i v_b}{v_i} = \frac{-10^4(-10)}{5} = 2 \times 10^4\ \Omega$$

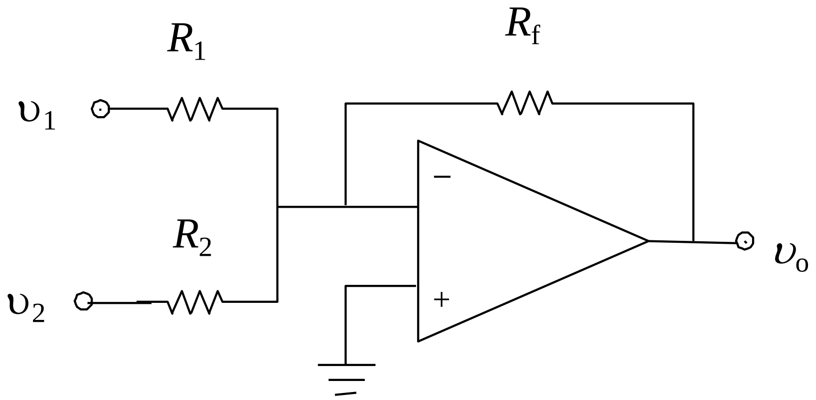
For a gain of - 10, R_f / R_i =10; or R_f= 100 kΩ . The circuit equation is

$$v_o = -R_f\left(\frac{v_i}{R_i} + \frac{v_b}{R_b}\right)$$

$$v_o = -10^5\left(\frac{v_i}{10^4} + \frac{v_b}{2 \times 10^4}\right)$$

$$v_o = -10\left(v_i + \frac{v_b}{2}\right)$$

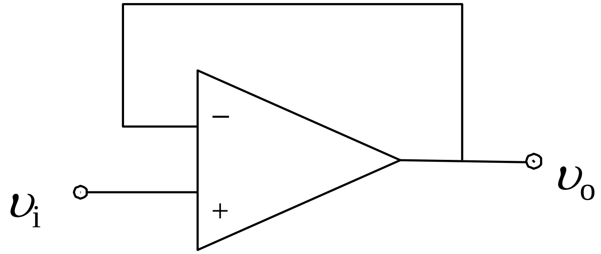
Summing Amplifier



$$v_o = -R_f\left(\frac{v_1}{R_1} + \frac{v_2}{R_2}\right)$$

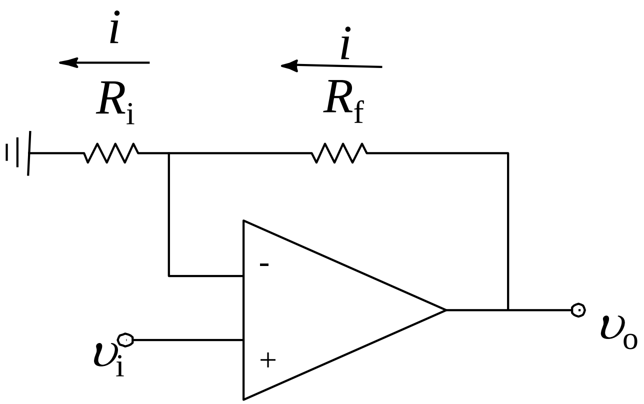
Follower (buffer)

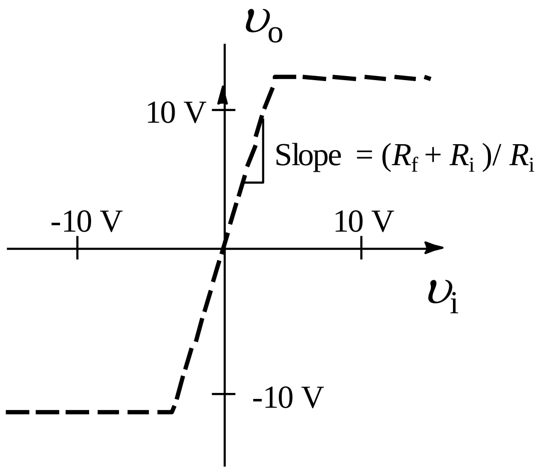
Used as a buffer, to prevent a high source resistance from being loaded down by a low-resistance load. In another word it prevents drawing current from the source.



$$v_o = v_i \qquad\qquad G = 1$$

Noninverting Amplifier



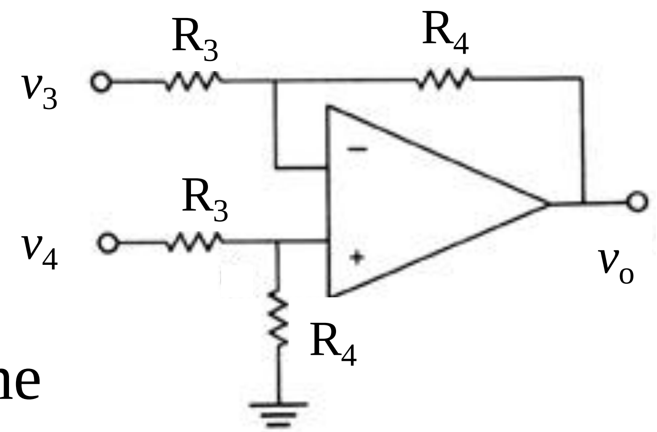


$$v_o = \frac{R_f + R_i}{R_i} v_i \qquad G = \frac{R_f + R_i}{R_i} = \left(1 + \frac{R_f}{R_i}\right)$$

Differential Amplifiers

Differential Gain G_d

$$G_d = \frac{v_o}{v_4 - v_3} = \frac{R_4}{R_3}$$



Common Mode Gain G_c

For ideal op amp if the inputs are equal then the output = 0, and the G_c =0. No differential amplifier perfectly rejects the common-mode voltage.

$$v_o = \frac{R_4}{R_3}(v_4 - v_3)$$

Common-mode rejection ratio *CMMR*

$$CMRR = \frac{G_d}{G_c}$$

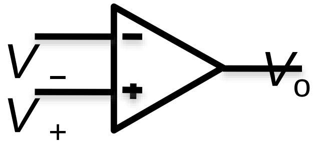
Typical values range from 100 to 10,000

Disadvantage of one-op-amp differential amplifier is its low input resistance

➢ Common-mode rejection ratio

- The **common-mode rejection ratio** (CMRR) of a differential amplifier (or other device) measures the tendency of the device to reject input signals common to both input leads.

- Ideally, a differential amplifier takes the voltages V_+ and V_- on its two inputs and produces an output voltage $V_o = A_d(V_+ - V_-)$, where A_d is the differential gain.



- However, the output of a real differential amplifier is better described as

$$V_o = A_d(V_+ - V_-) + \frac{1}{2}A_s(V_+ + V_-),$$

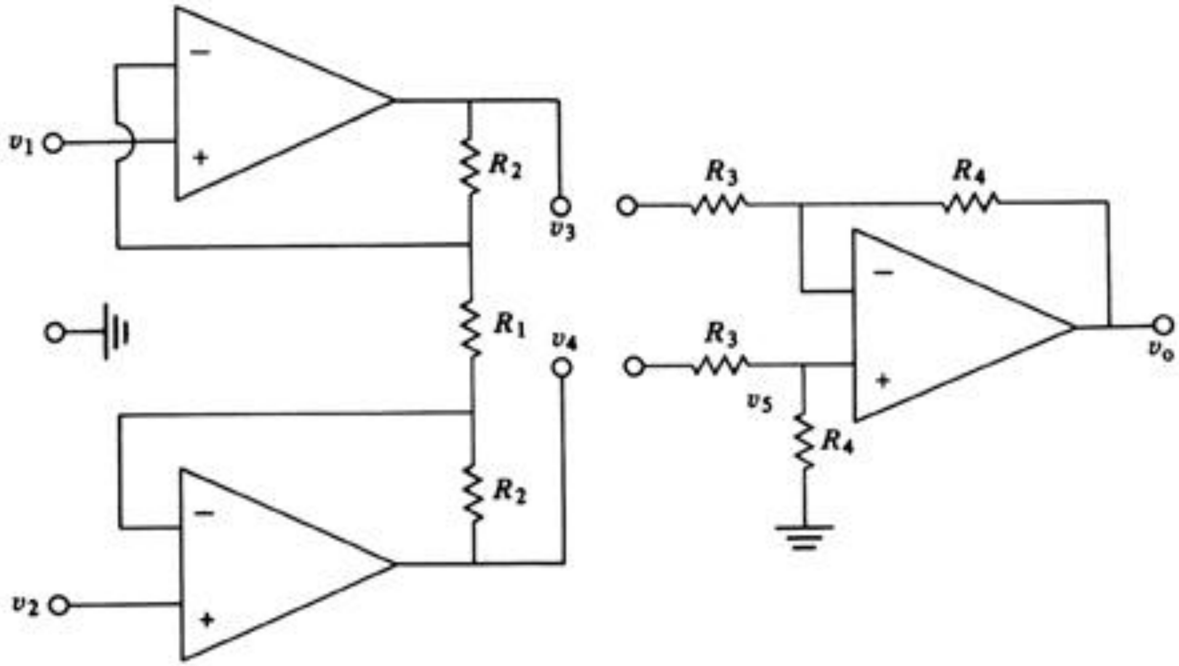
where As is the common-mode gain, which is typically much smaller than the differential gain.

- The CMRR is defined as the ratio of the powers of the differential gain over the common-mode gain, measured in positive decibels (thus using the 20 log rule):

$$\mathrm{CMRR} = 10\log_{10}\left(\frac{A_d}{A_s}\right)^2 = 20\log_{10}\left(\frac{A_d}{|A_s|}\right)$$

- **The CMRR of the measurement instrument determines the attenuation applied to the offset or noise.**

Instrumentation Amplifiers



Differential Mode Gain

$$v_3 - v_4 = i(R_2 + R_1 + R_2)$$

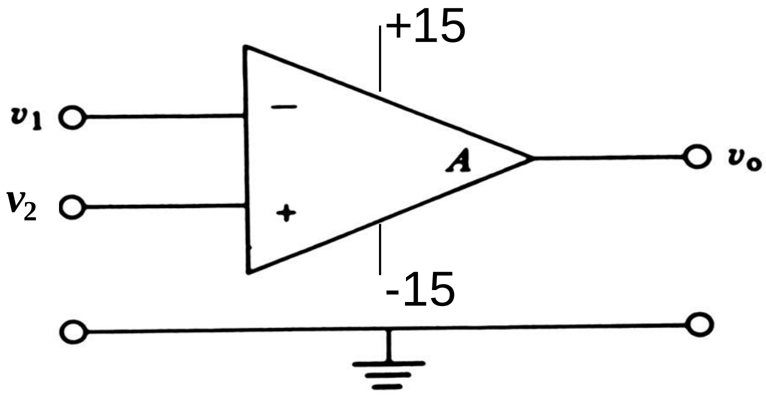
$$v_1 - v_2 = iR_1$$

$$G_d = \frac{v_3 - v_4}{v_1 - v_2} = \frac{2R_2 + R_1}{R_1}$$

$$v_o = \left(\frac{2R_2 + R_1}{R_1}\right)\frac{R_4}{R_3}(v_2 - v_1)$$

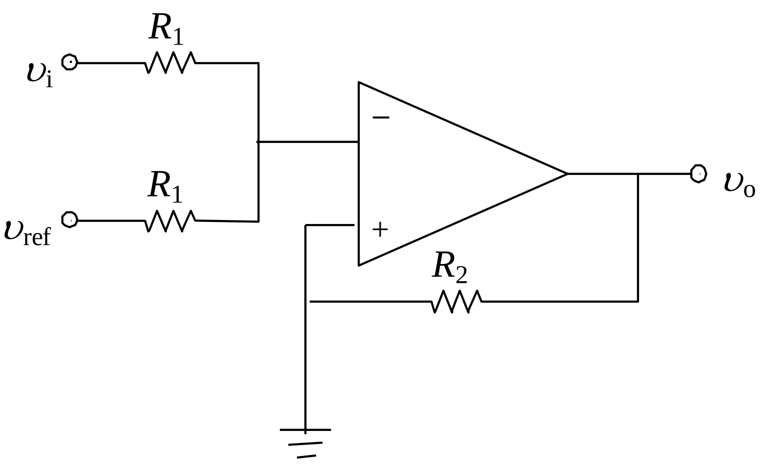
Advantages: High input impedance, a high CMRR, Variable gain

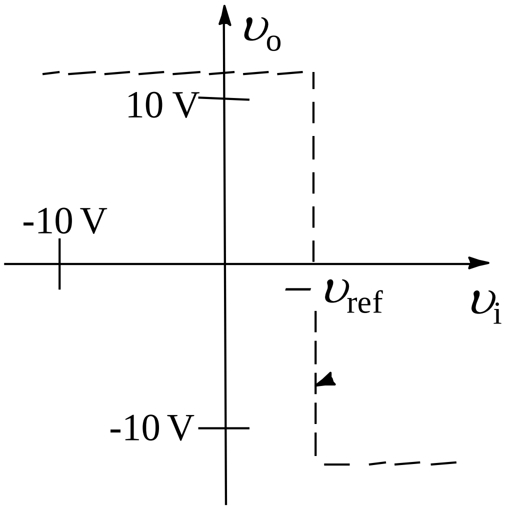
Comparator – No Hysteresis



$v_1 > v_2$, v_o = -13 V

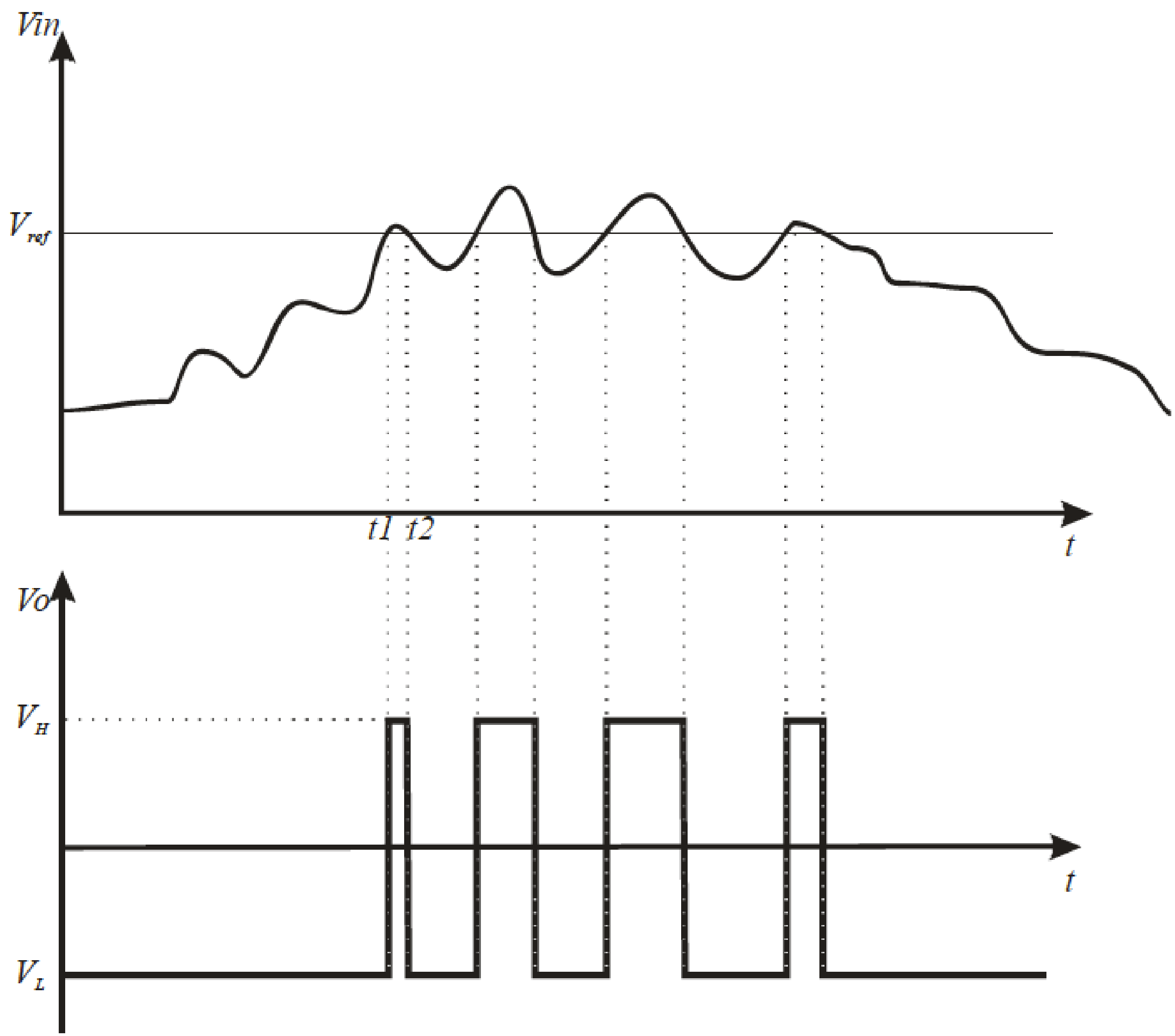
$v_1 < v_2$, v_o = +13 V





If $(v_i+v_{ref}) > 0$ then v_o = -13 V else v_o = +13 V

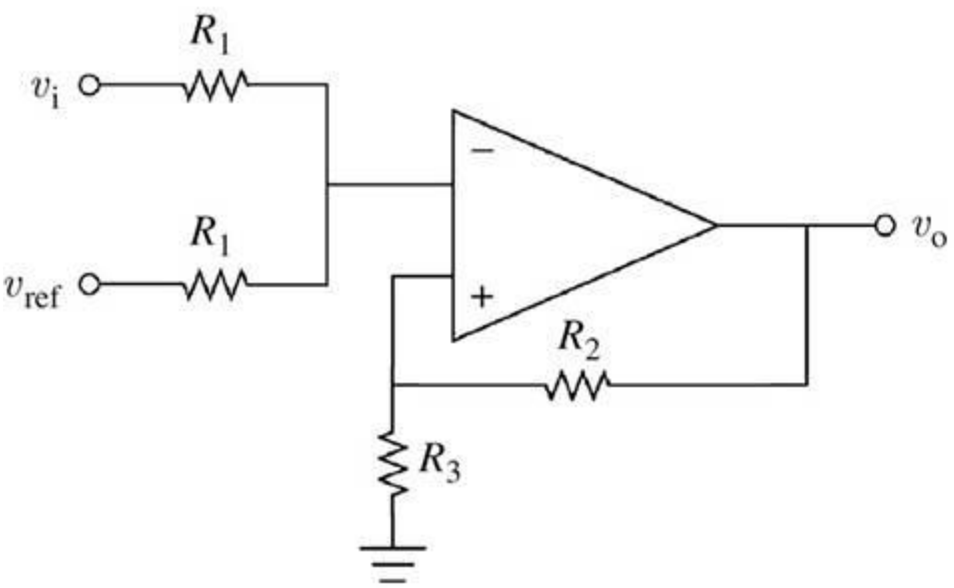
R_1 will prevent overdriving the op-amp



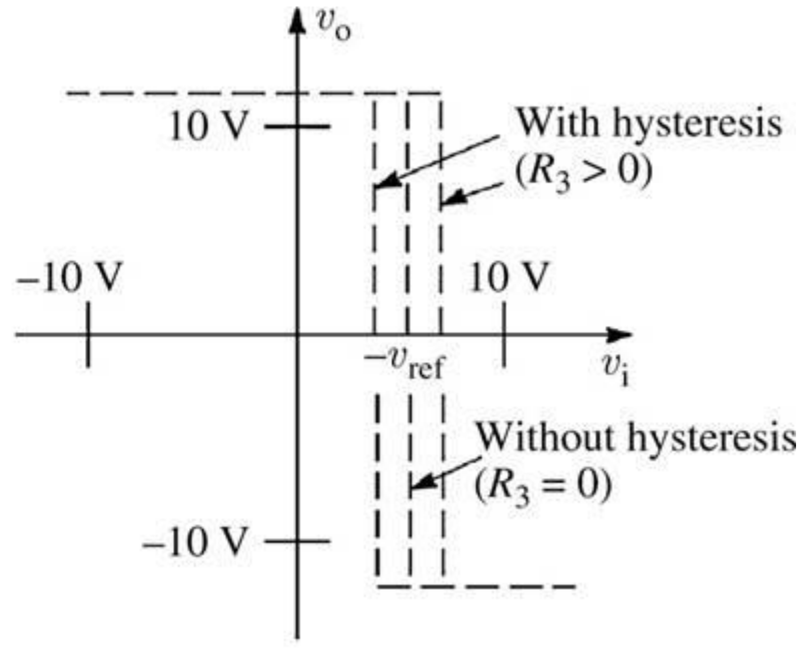
Note that as V_{in} exceeds V_{ref}, the voltage at the output of the comparator switches from V_L to V_H Notice that sometime after t_1 the voltage V_{in} begins to decrease and at time t_2 is crosses V_{ref} . Now the output of the comparator switches back to V_L. This fluctuation in *Vin* might be noise in the signal.

Comparator – With Hysteresis

Reduces multiple transitions due to mV noise levels by moving the threshold value after each transition.

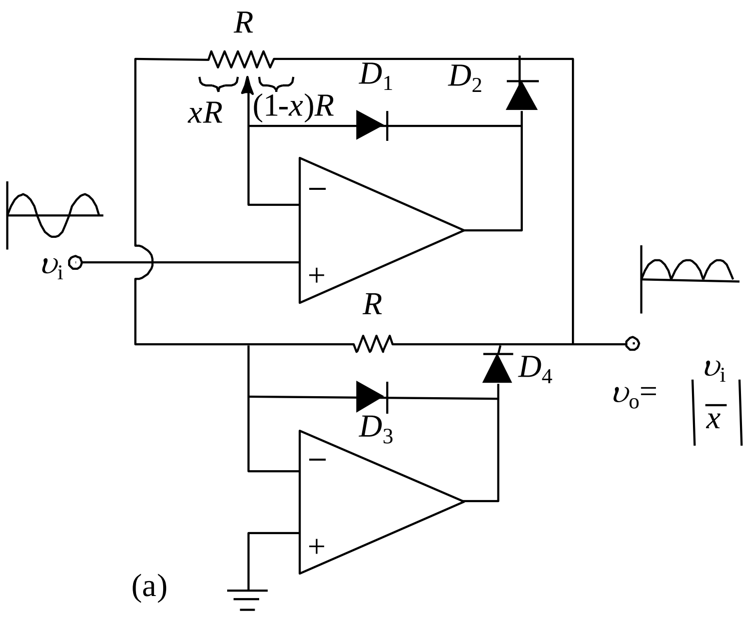


(a)

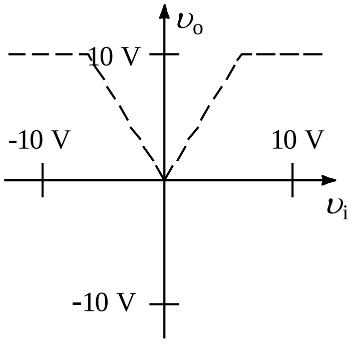


(b)

Rectifier



(a)



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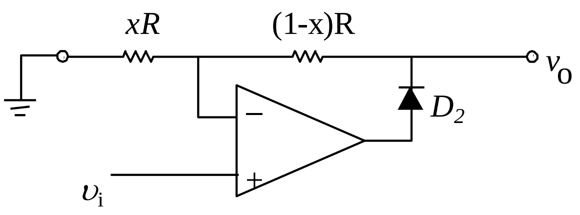


(a)

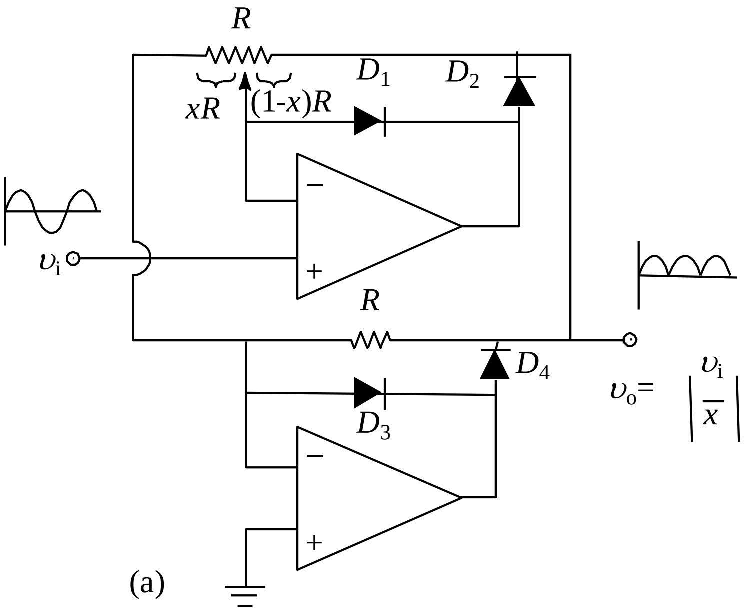
Full-wave precision rectifier:

a) For $\upsilon_i > 0$,

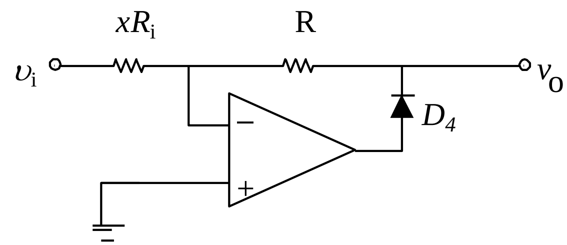
D_2 and D_3 conduct, whereas D_1 and D_4 are reverse-biased.

Noninverting amplifier at the top is active

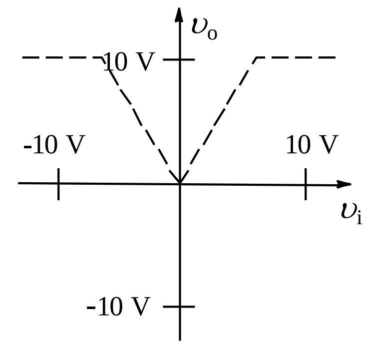
Rectifier



(a)



(b)



(b)

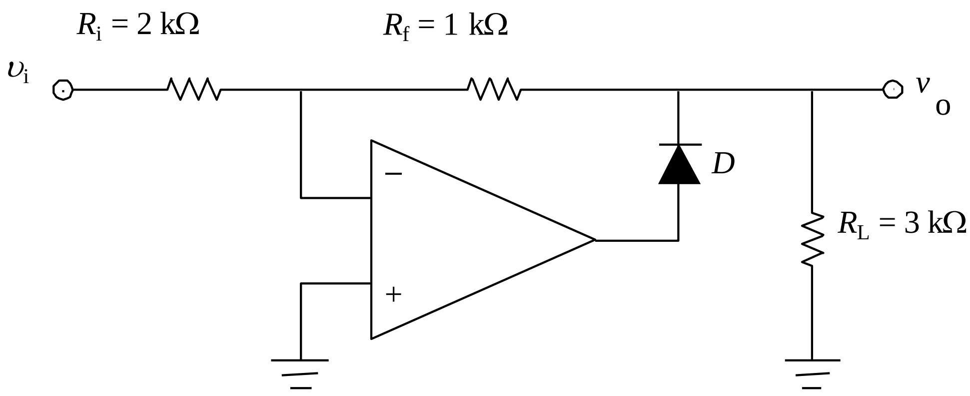
Full-wave precision rectifier:

b) For $\upsilon_i < 0$,

D_1 and D_4 conduct, whereas D_2 and D_3 are reverse-biased.

Inverting amplifier at the bottom is active

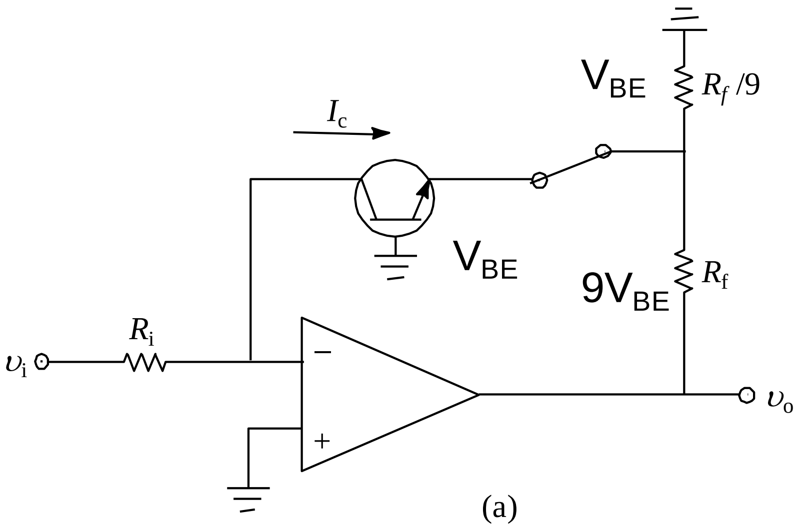
One-Op-Amp Full Wave Rectifier



(c)

For $\upsilon_i < 0$, the circuit behaves like the inverting amplifier rectifier with a gain of +0.5. For $\upsilon_i > 0$, the op amp disconnects and the passive resistor chain yields a gain of +0.5.

Logarithmic Amplifiers



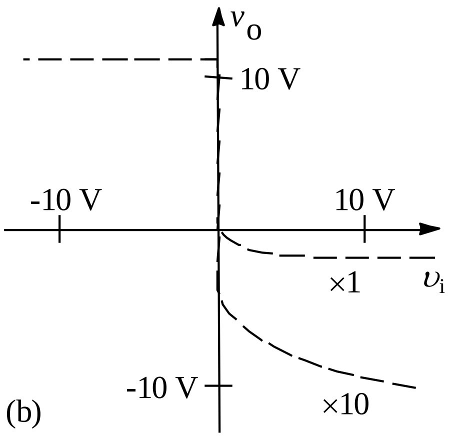


Figure 3.8 (a) With the switch thrown in the alternate position, the circuit gain is increased by 10. (b) Input-output characteristics show that the logarithmic relation is obtained for only one polarity; ×1 and ×10 gains are indicated.

Integrators

what if we were to change the purely resistive (Rf) feedback element of an inverting amplifier to that of a frequency dependEnt impedance such as a Capacitor, C. What would be the effect on the op-amps output voltage over its frequency range?

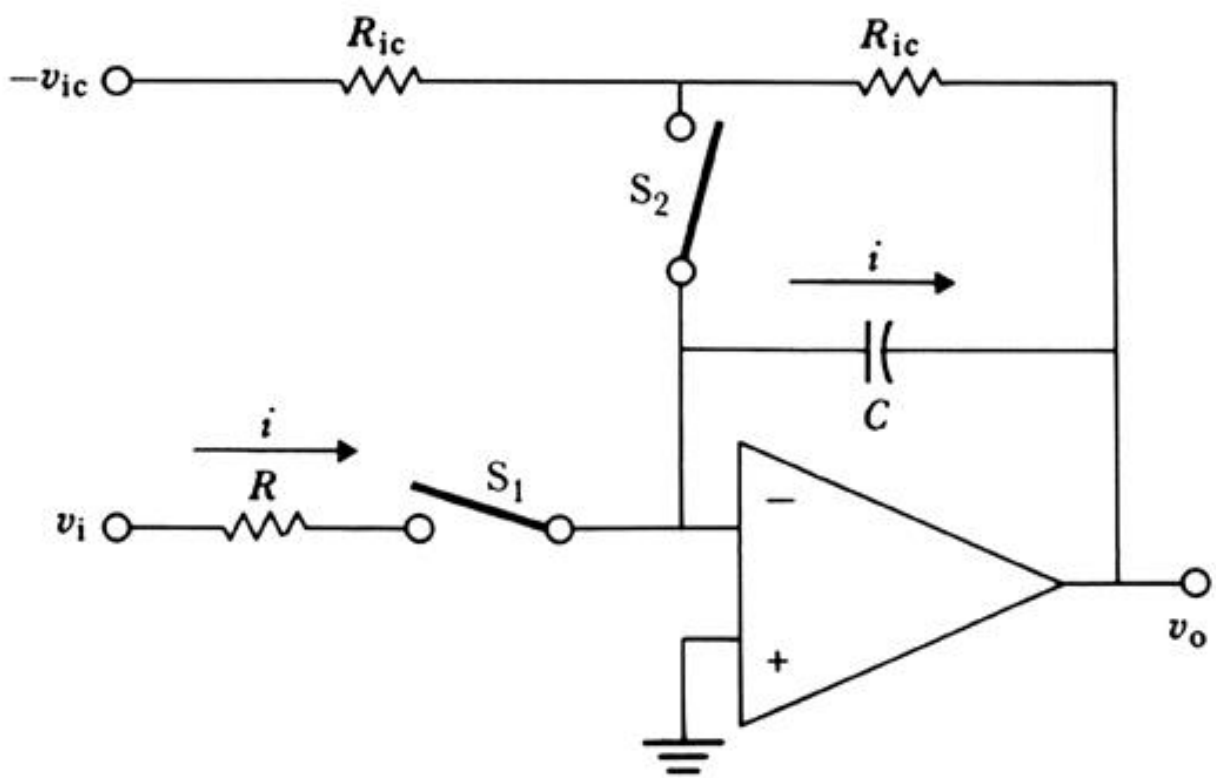


Figure 3.9 A three-mode integrator With S_1 open and S_2 closed, the dc circuit behaves as an inverting amplifier. Thus $\upsilon_o = \upsilon_{ic}$ and υ_o can be set to any desired initial conduction. **With S_1 closed and S_2 open, the circuit integrates.** With both switches open, the circuit holds υ_o constant, making possible a leisurely readout.

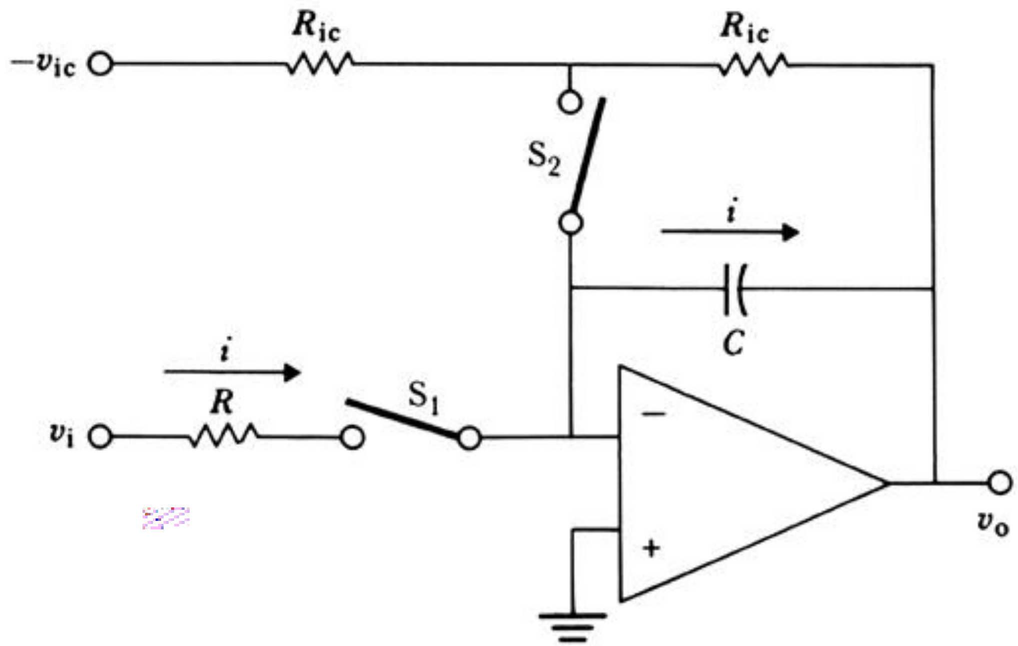
Integrators– (cont.)

$$v_o = -\frac{1}{R_i C_f}\int_0^{t_1} v_i\,dt + v_{ic}$$

$$\frac{V_o(j\omega)}{V_i(j\omega)} = -\frac{Z_f}{Z_i}$$

$$\frac{V_o(jw)}{V_i(jw)} = \frac{-1/jwc}{R_i}$$

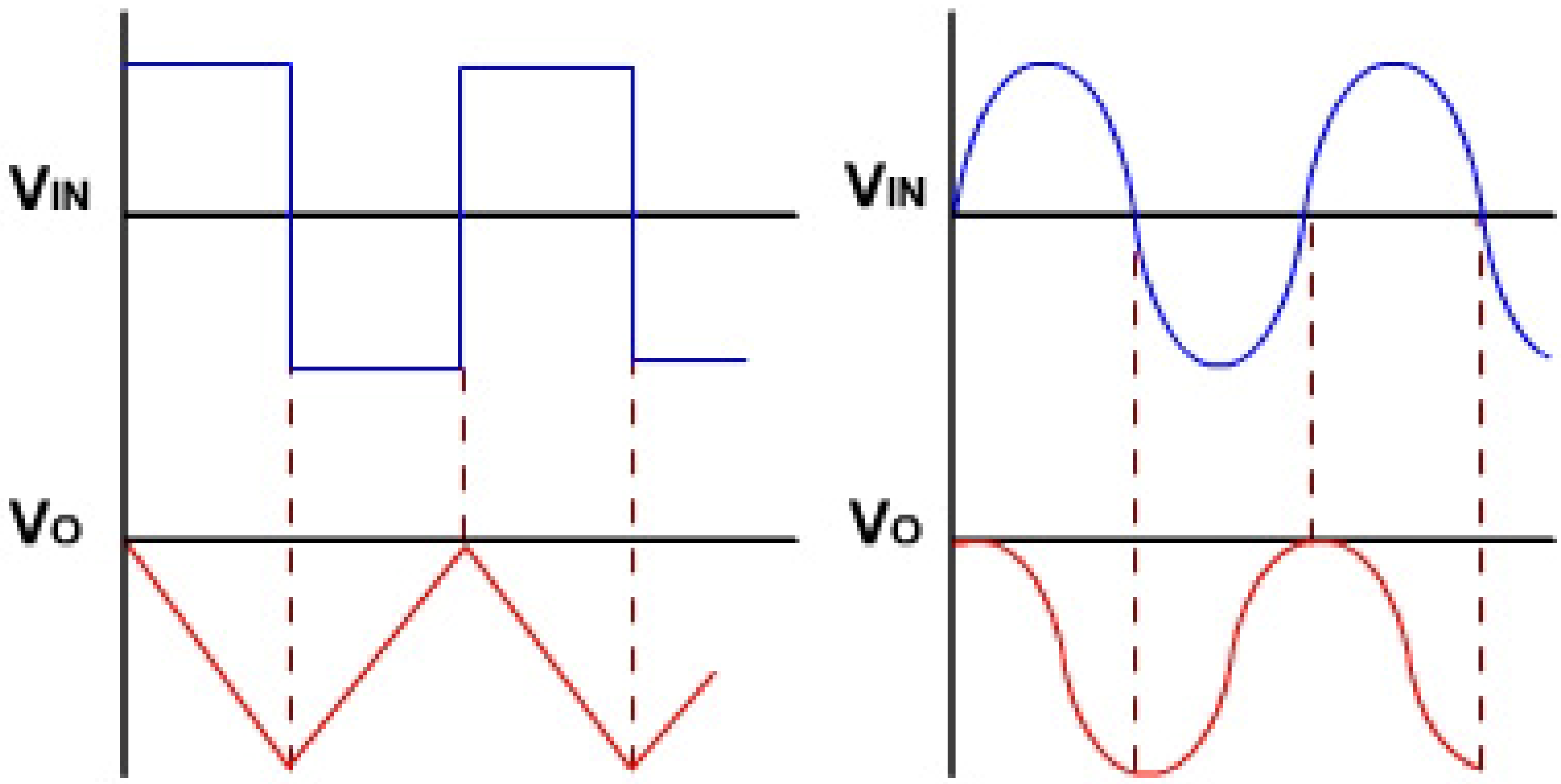
$$\frac{V_o(jw)}{V_i(jw)} = \frac{-1}{jwR_iC} = \frac{-1}{jwt}$$



- circuit gain decreases as R increases
- circuit gain is 1 when ωτ = 1

- The output voltage is directly proportional to the negative integral of the input voltage and inversely proportional to the time constant RC.

- If the input is a sine wave the output will be cosine wave. If the input is a square wave, the output will be a triangular wave.



- An integrator circuit produces a steadily changing output voltage for a constant input voltage.

Differentiators

- produces a voltage output which is directly proportional to the input voltage's rate-of-change with respect to time

$$v_o = -RC\frac{dv_i}{dt}$$

$$\frac{V_o(j\omega)}{V_i(j\omega)} = -\frac{Z_f}{Z_i} = -j\omega RC$$

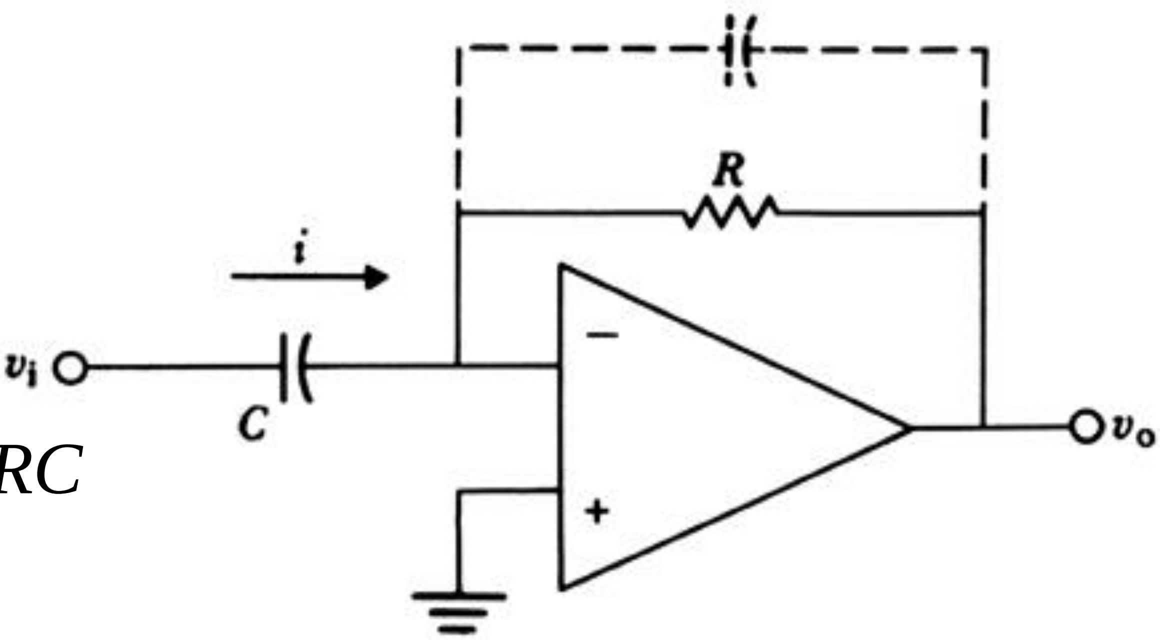
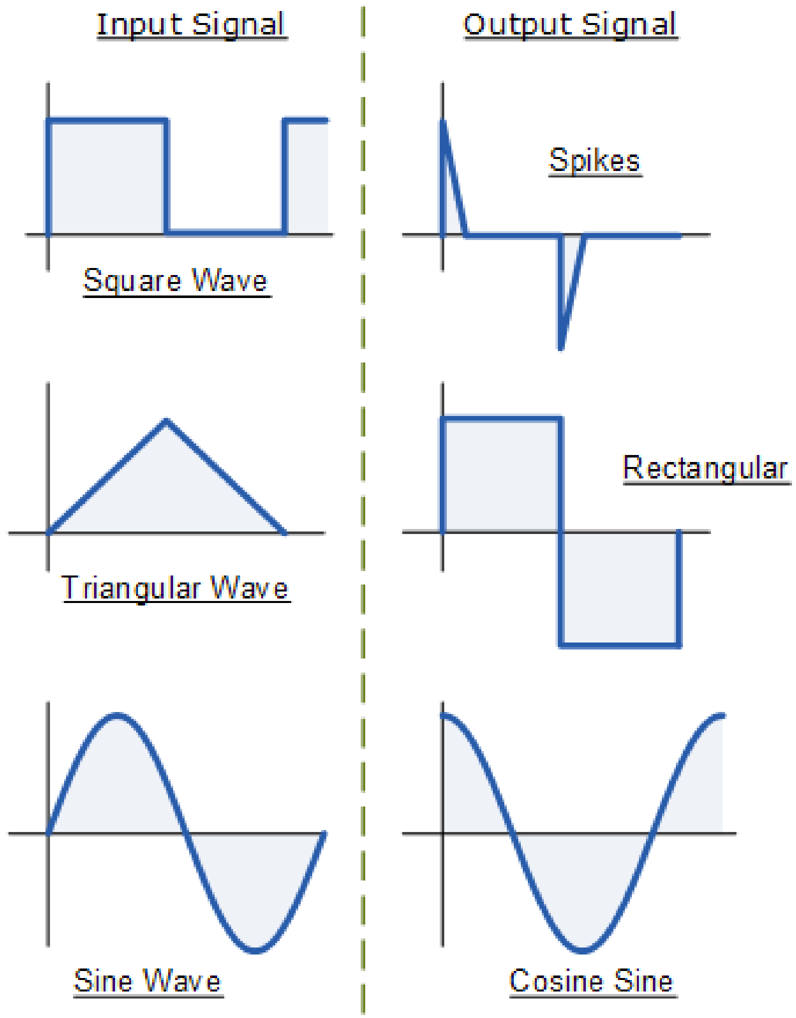


Figure 3.11 A differentiator The dashed lines indicate that a small capacitor must usually be added across the feedback resistor to prevent oscillation.

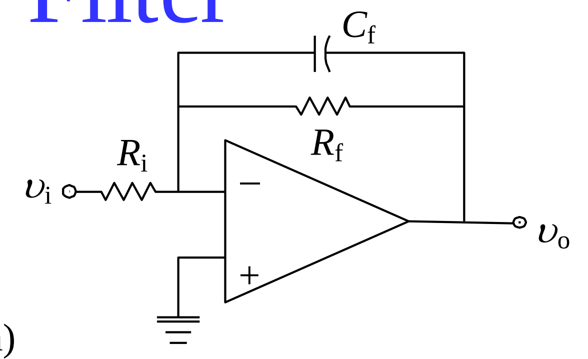
Op-amp Differentiator Waveforms



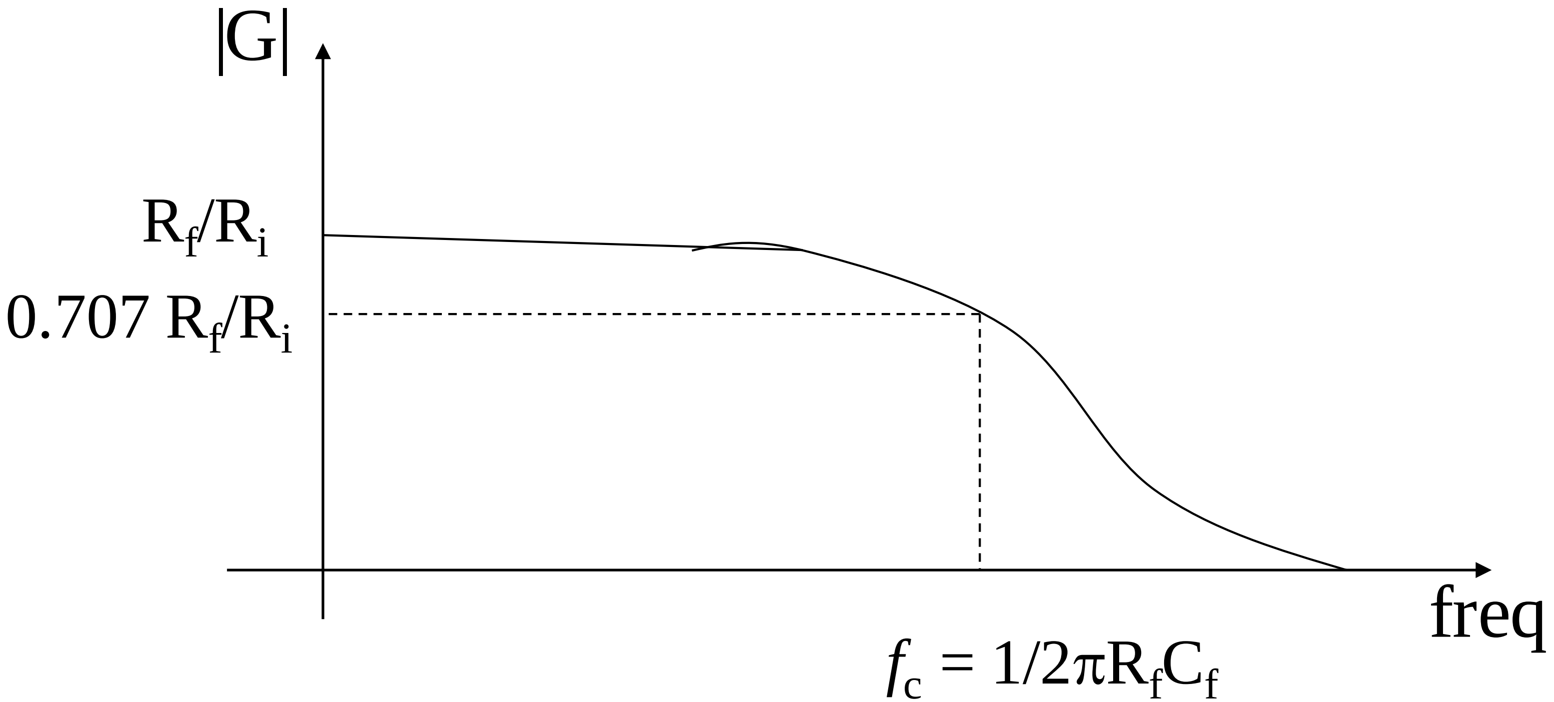
- A differentiator circuit produces a constant output voltage for a steadily changing input voltage.

Active Filters- Low-Pass Filter

$$\text{Gain} = G = \frac{V_o(j\omega)}{V_i(j\omega)} = \frac{-R_f}{R_i}\frac{1}{1 + j\omega R_f C_f}$$



(a)

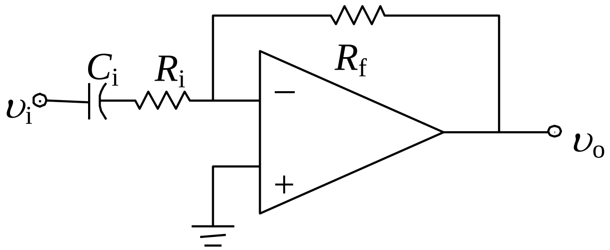


Active filters

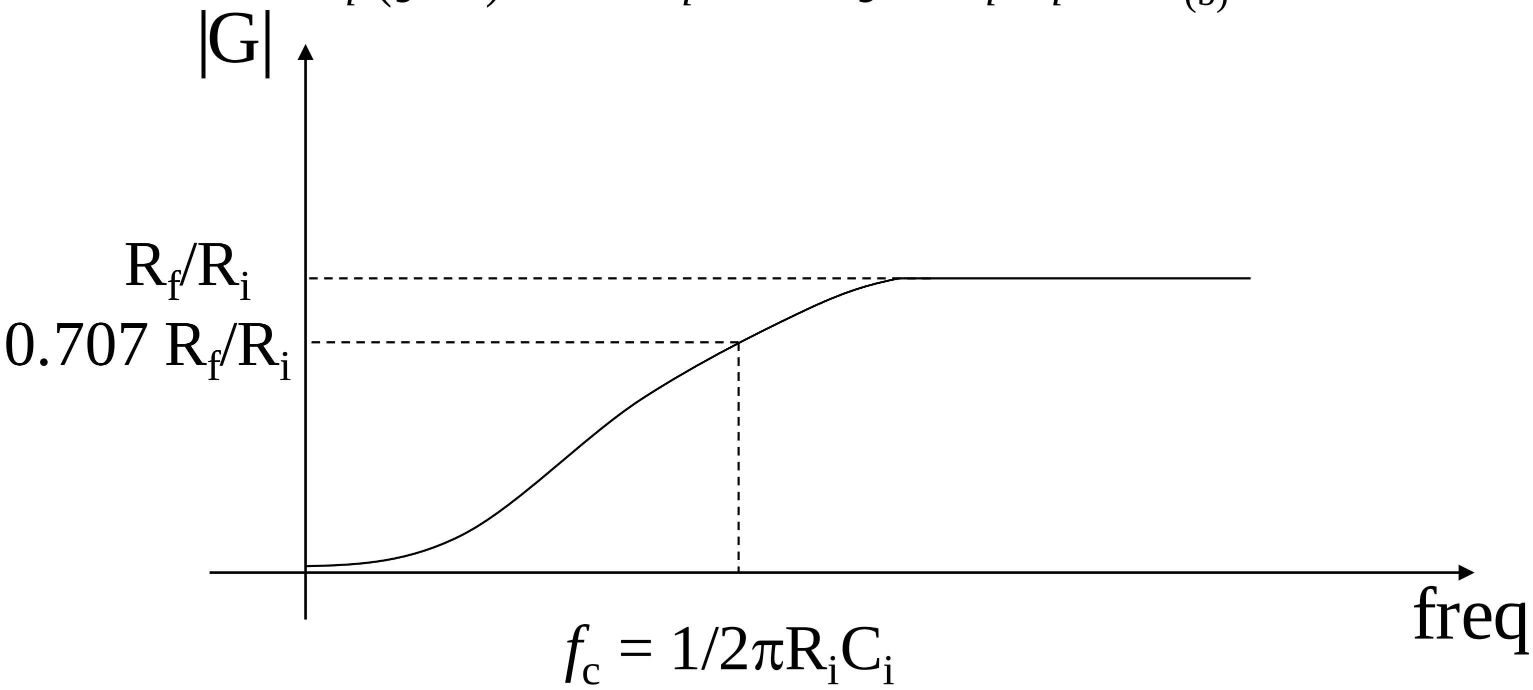
(a) A low-pass filter attenuates high frequencies

Active Filters (High-Pass Filter)

$$\text{Gain} = G = \frac{V_o(j\omega)}{V_i(j\omega)} = \frac{-R_f}{R_i}\,\frac{j\omega R_i C_i}{1 + j\omega R_i C_i}$$



(b)

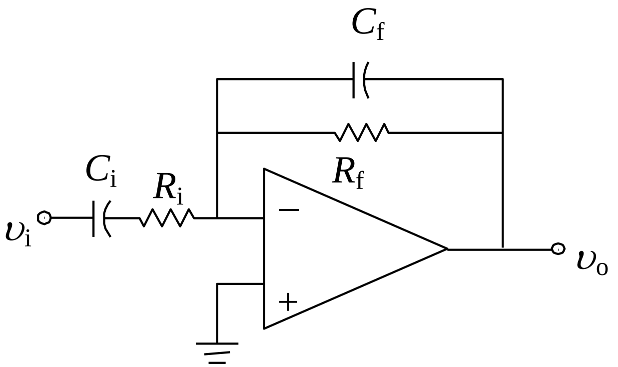


Active filters

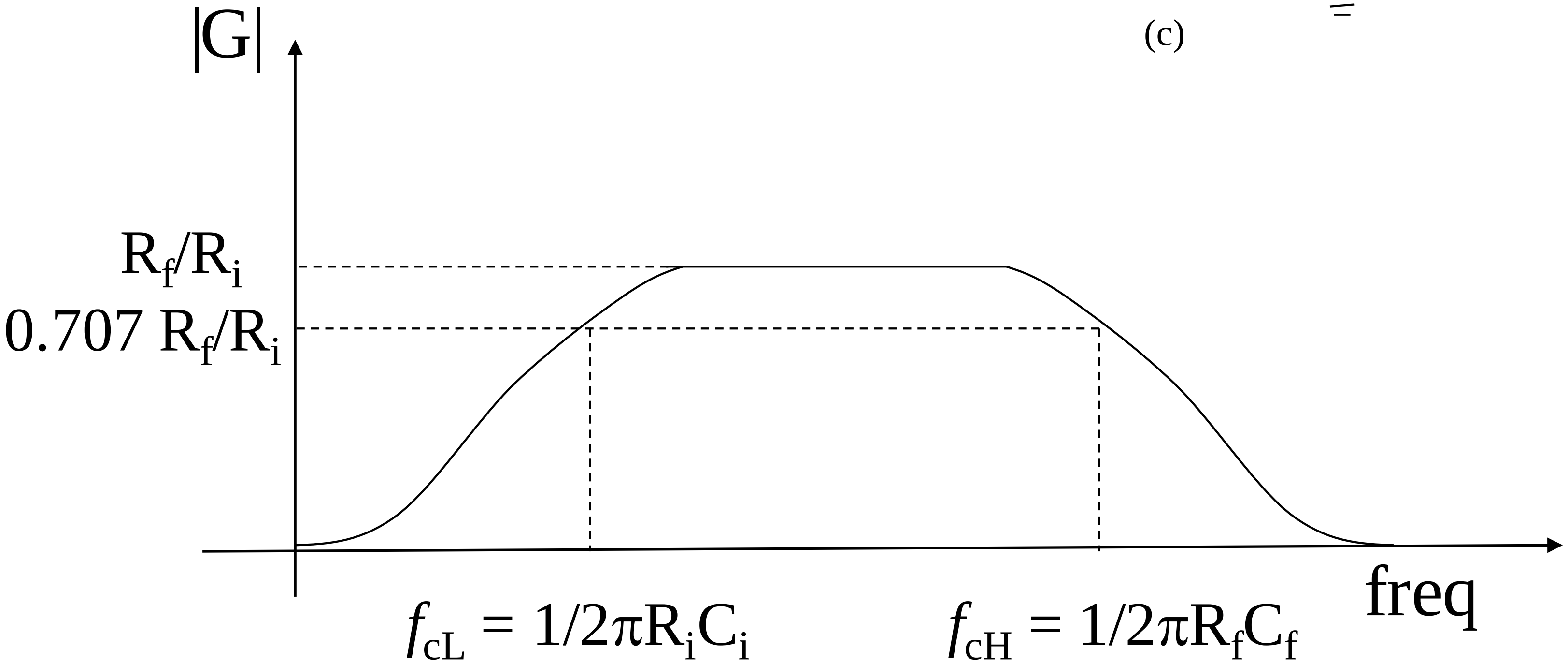
(b) A high-pass filter attenuates low frequencies and blocks dc.

Active Filters (Band-Pass Filter)

$$\frac{V_o(j\omega)}{V_i(j\omega)} = \frac{-j\omega R_f C_i}{\left(1 + j\omega R_f C_f\right)\left(1 + j\omega R_i C_i\right)}$$



(c)



Active filters

(c) A bandpass filter attenuates both low and high frequencies.

Frequency Response of op-amp and Amplifier

Open-Loop Gain
Compensation
Closed-Loop Gain
Gain Bandwidth Product
Slew Rate

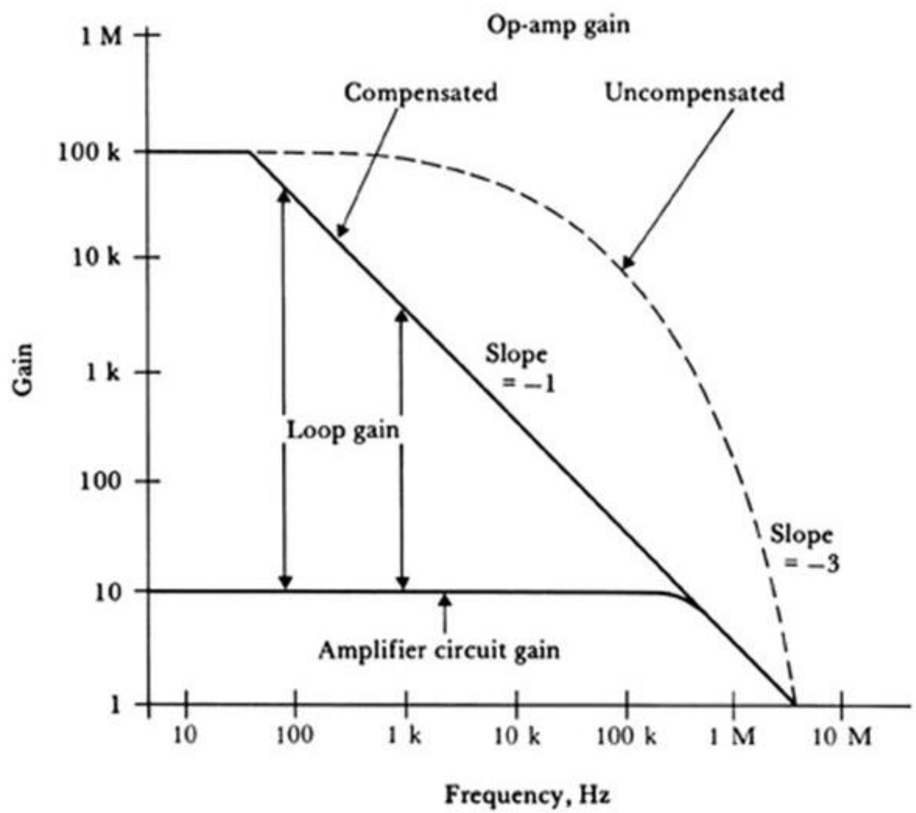


Figure 3.13 Op-amp frequency characteristics early op amps (such as the 709) were uncompensated, had a gain greater than 1 when the phase shift was equal to –180°, and therefore oscillated unless compensation was added externally. A popular op amp, the 411, is compensated internally, so for a gain greater than 1, the phase shift is limited to –90°. When feedback resistors are added to build an amplifier circuit, the loop gain on this log-log plot is the difference between the op-amp gain and the amplifier-circuit gain.

Offset Voltage and Bias Current

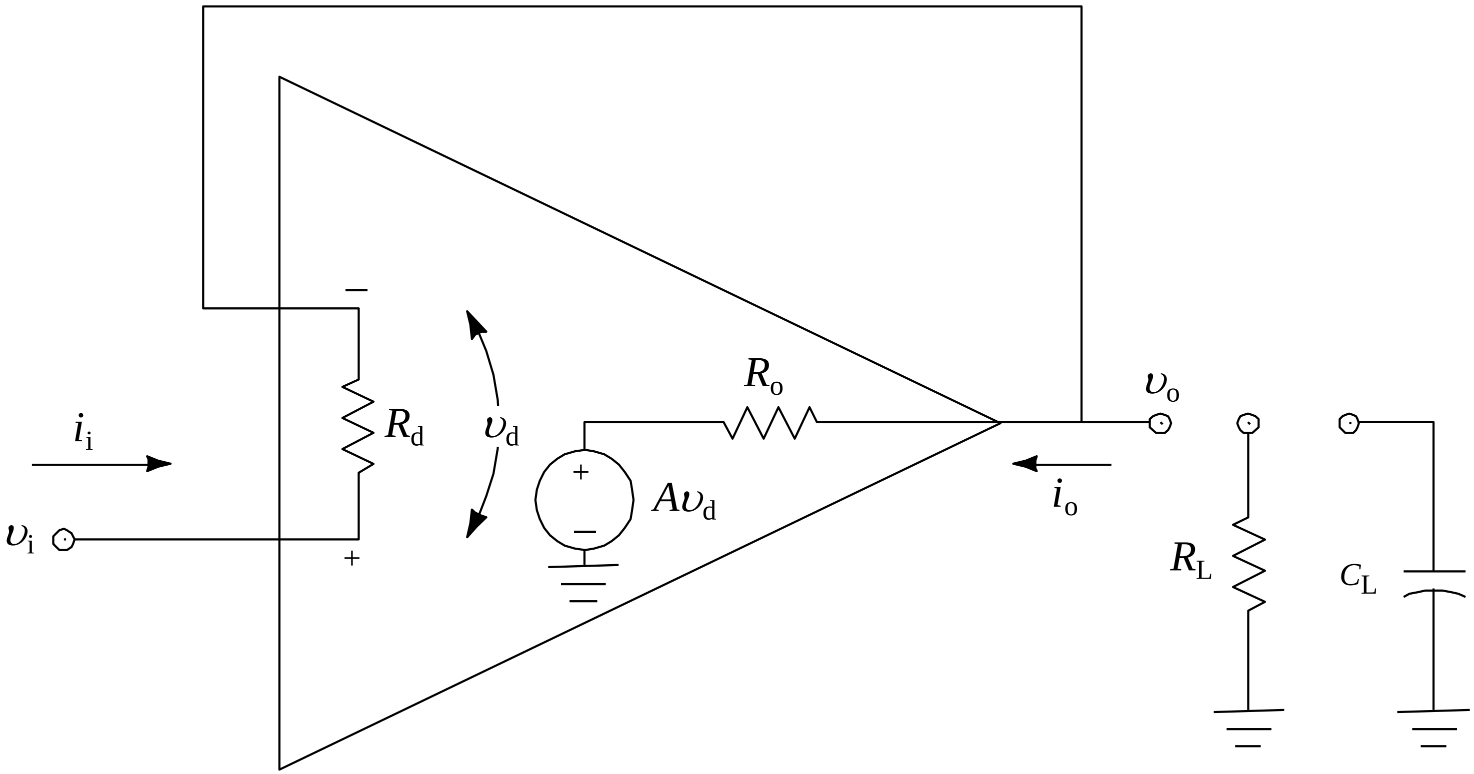
Read section 3.12 (OFFSET VOLTAGE)

Nulling, Drift, Noise

Read section and 3.13 (BIAS CURRENT)

Differential bias current, Drift, Noise

Input and Output Resistance



$$R_{ai} = \frac{\Delta v_i}{\Delta i_i} = (A+1)R_d$$

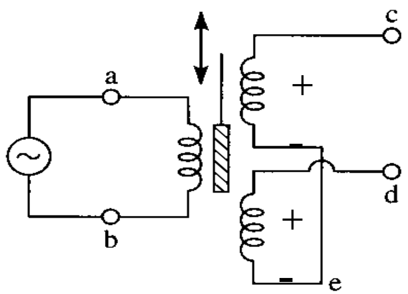
$$R_{ao} = \frac{\Delta v_o}{\Delta i_o} = \frac{R_o}{A+1}$$

Typical value of R_d = 2 to 20 MΩ

Typical value of R_o = 40 Ω

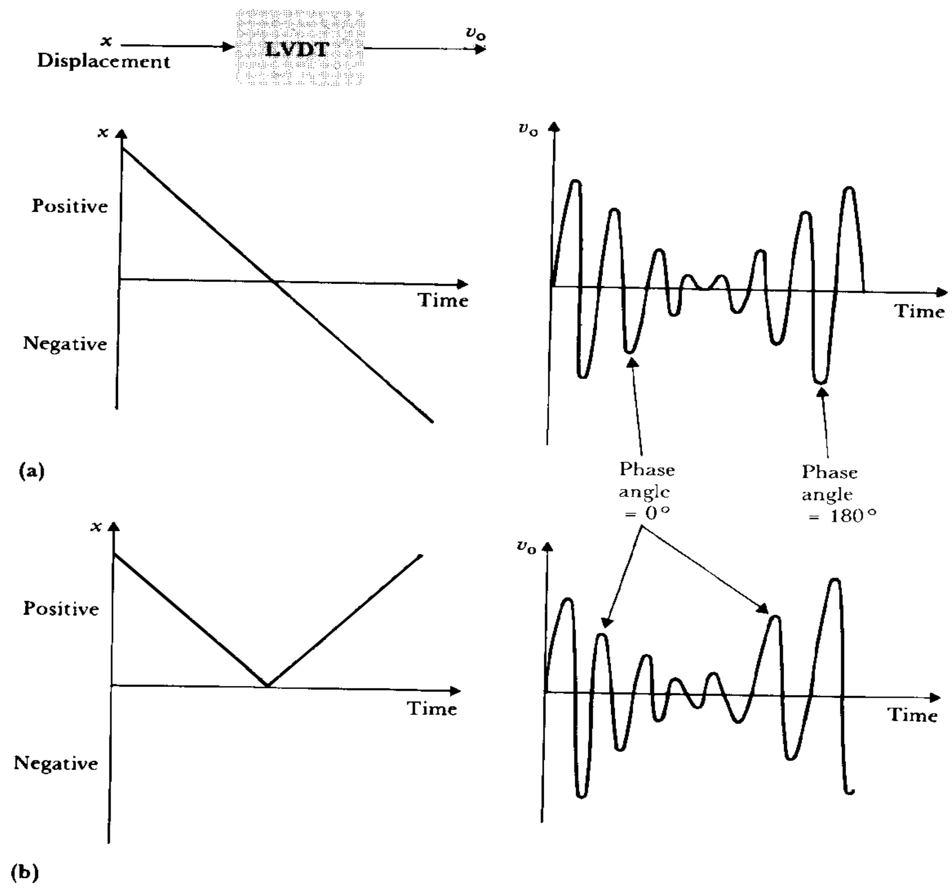
Phase Modulator for Linear variable differential transformer LVDT

- This device works on the principle that alterations in the self-inductance of a coil may be produced by changing the geometric form factor or the movement of a magnetic core within the coil.

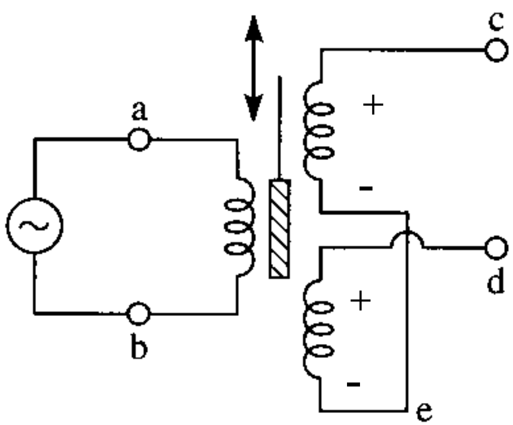


(c)

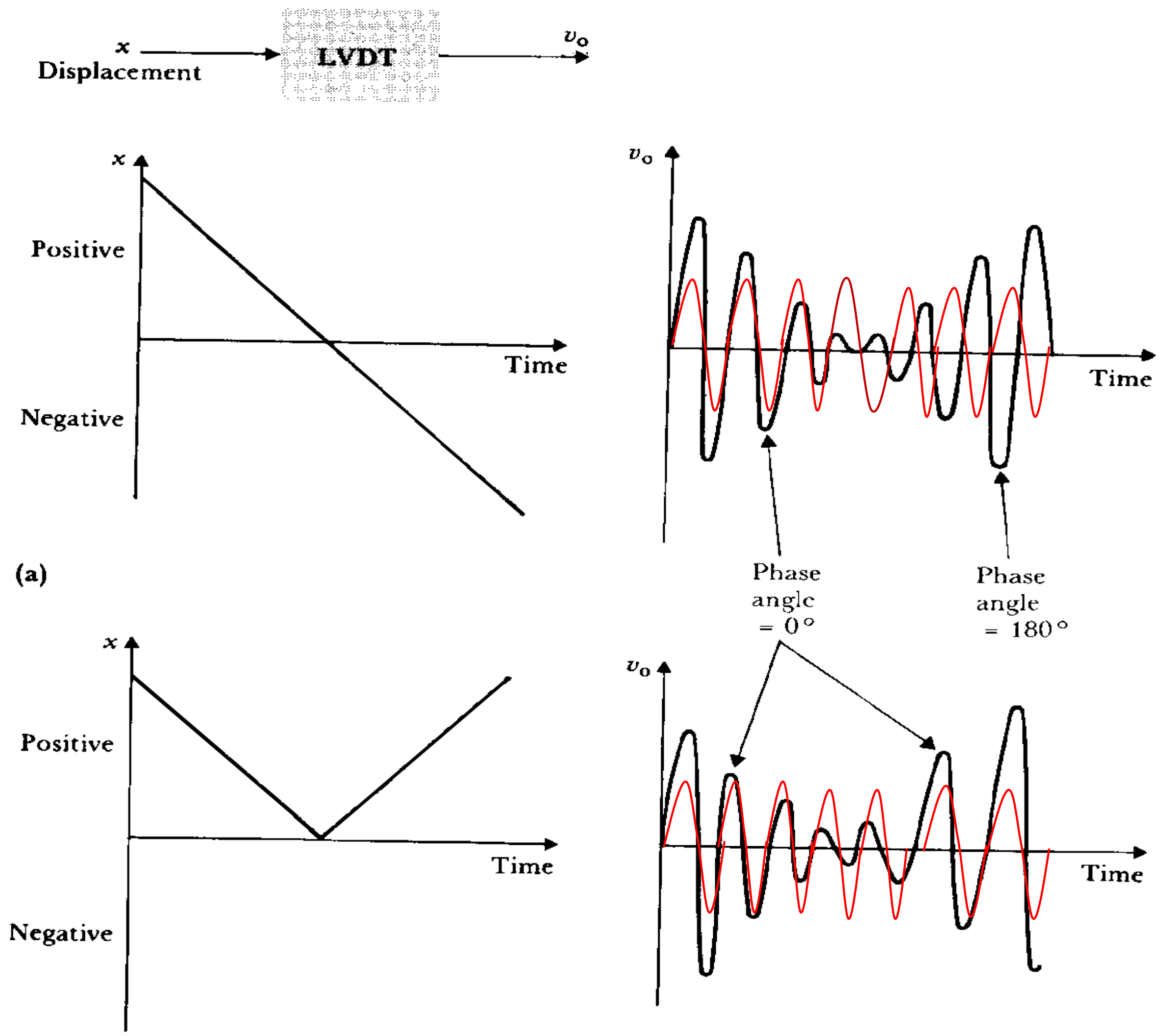
- **the same magnitude of output voltage results from two very different input displacements.**



Phase Modulator for Linear variable differential transformer LVDT



(c)



(a)

(b)

- The direction of displacement may be determined by using the fact that there is a 180° phase shift when the core passes through the null position

Phase-Sensitive Demodulator

- A phase-sensitive demodulator yields a full-wave-rectified output of the in-phase component of a sine wave. Its output is proportional to the amplitude of the input, but it changes sign when the phase shifts by 180° .

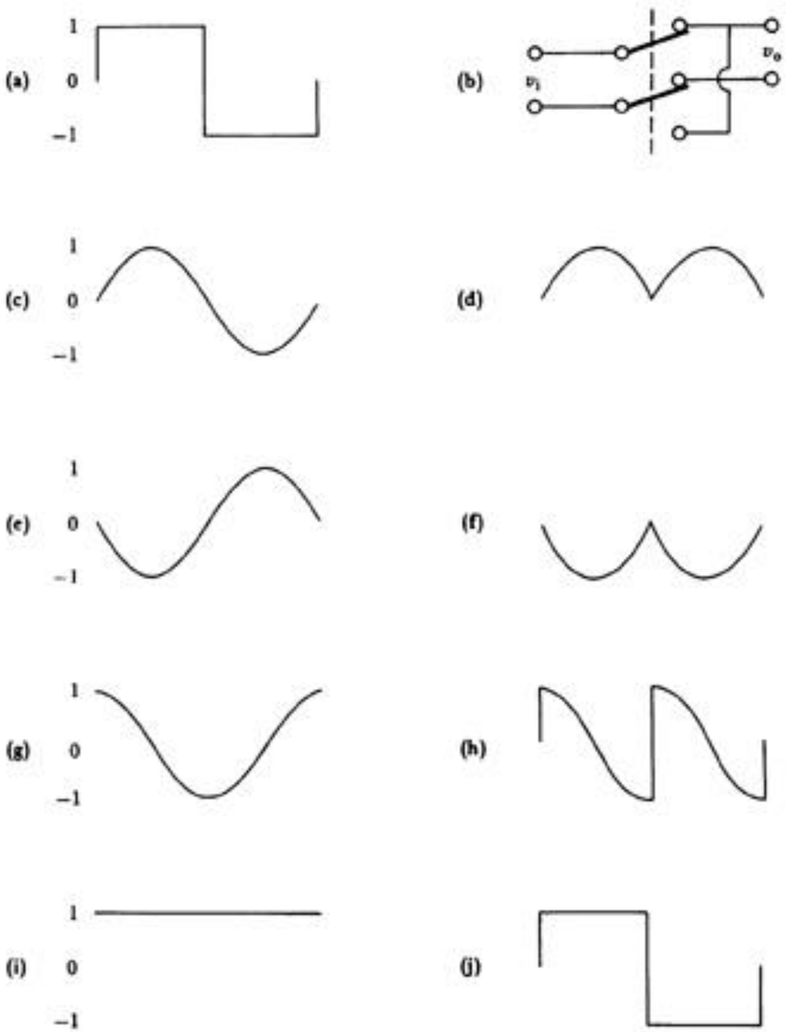


Figure 3.16 Functional operation of a phase-sensitive demodulator (a) Switching function. (b) Switch. (c), (e), (g), (i) Several input voltages. (d), (f), (h), (j) Corresponding output voltages.

Used in many medical instruments for signal detection, averaging, and Noise rejection