Operational amplifiers circuits design basics

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OPERATIONAL AMPLIFIERS (OP-AMP)

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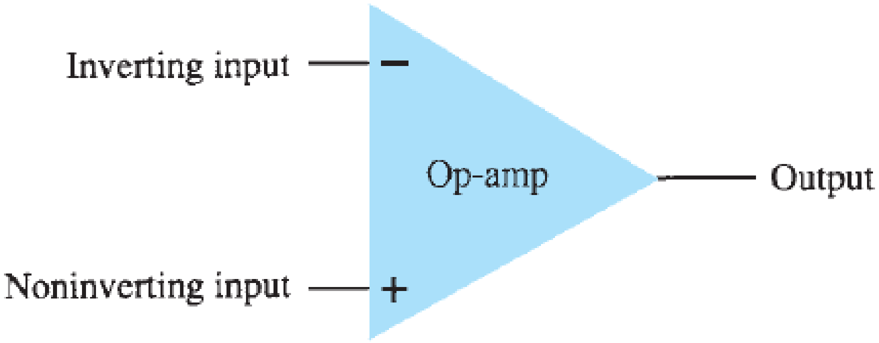
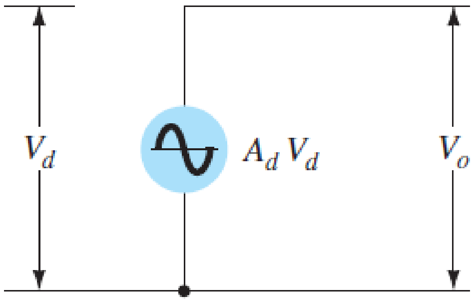
OP-AMP BASICS



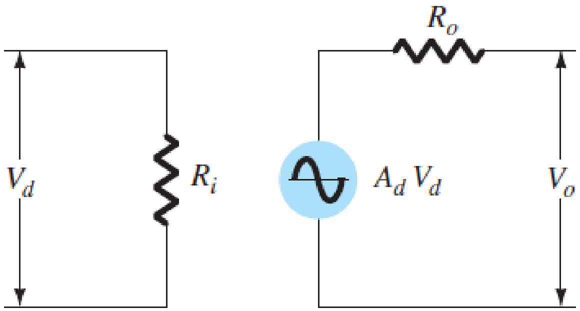
$$V_{out} = K(V_+ - V_-)$$

AC equivalent of op-amp circuit

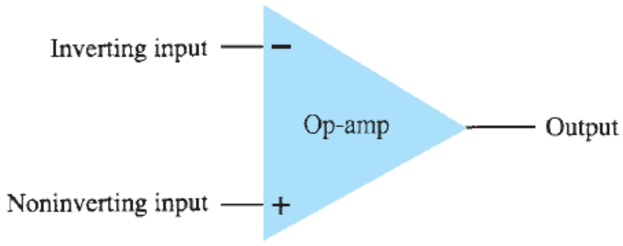
ideal



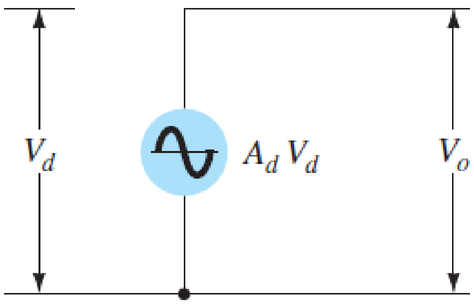
practical



Effect of Feedback Connection on Impedance



ideal



IDEAL OP AMP ATTRIBUTES

- ✓ Infinite Differential Gain
- ✓ Zero Common Mode Gain
- ✓ Zero Offset Voltage
- ✓ Zero Bias Current
- ✓ Infinite Bandwidth

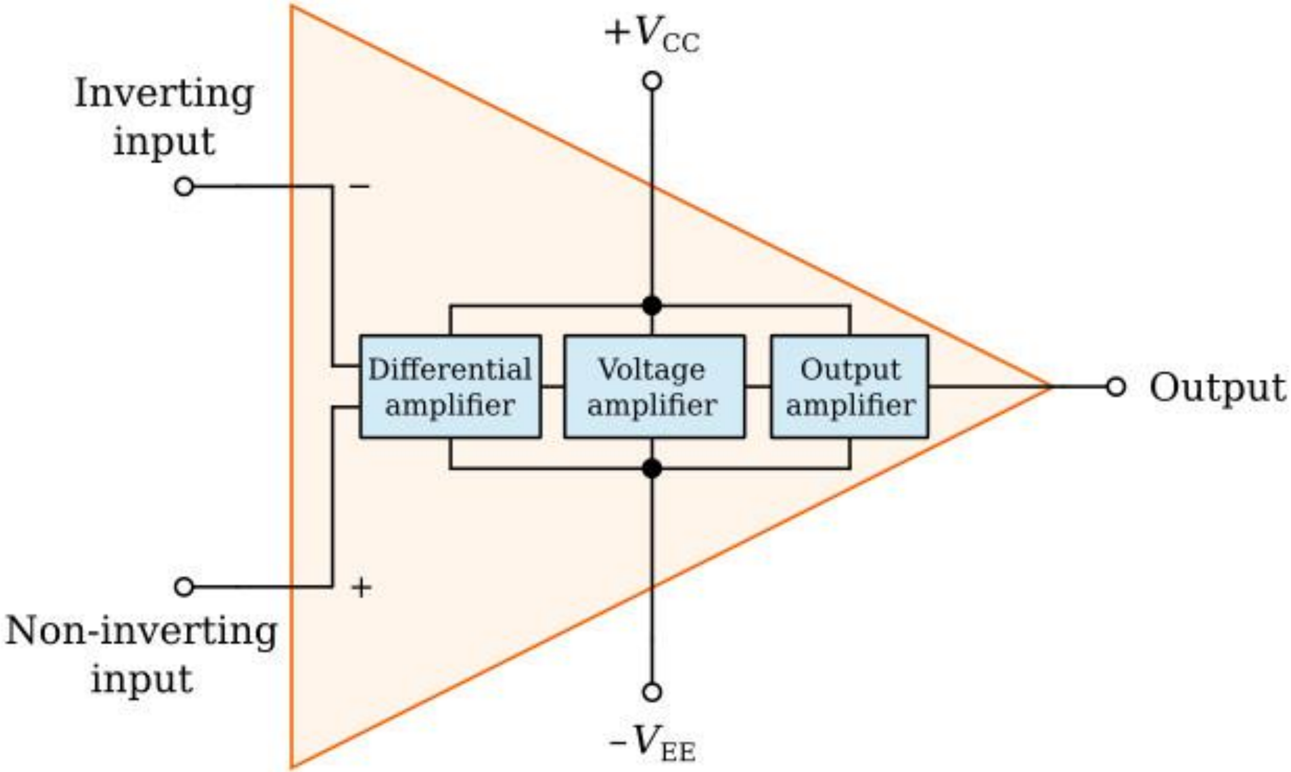
OP AMP INPUT ATTRIBUTES

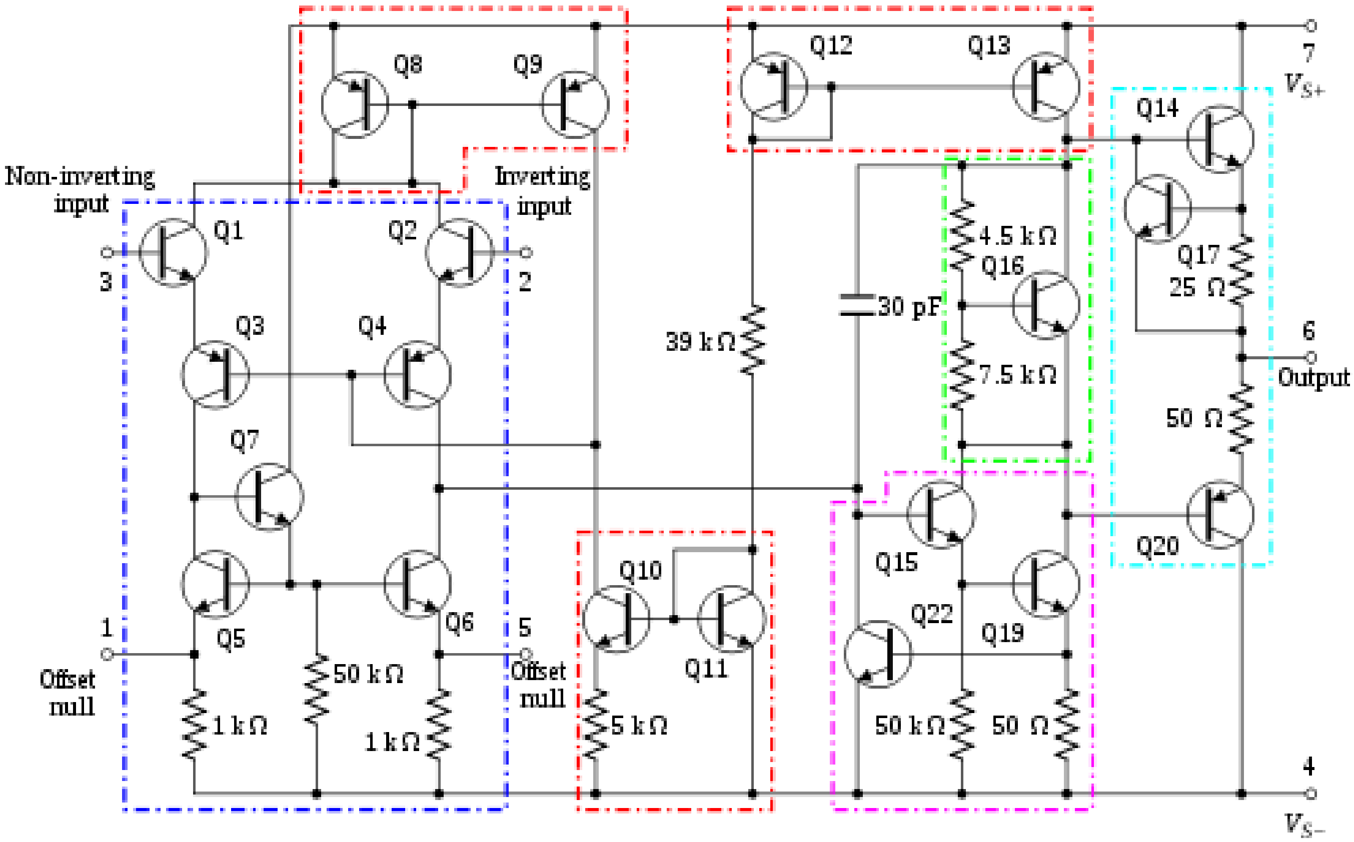
- ✓ Infinite Impedance
- ✓ Zero Bias Current
- ✓ Respond to Differential Voltages
- ✓ Do Not Respond to Common Mode Voltages

OP AMP OUTPUT ATTRIBITES

- ✓ Zero Impedance

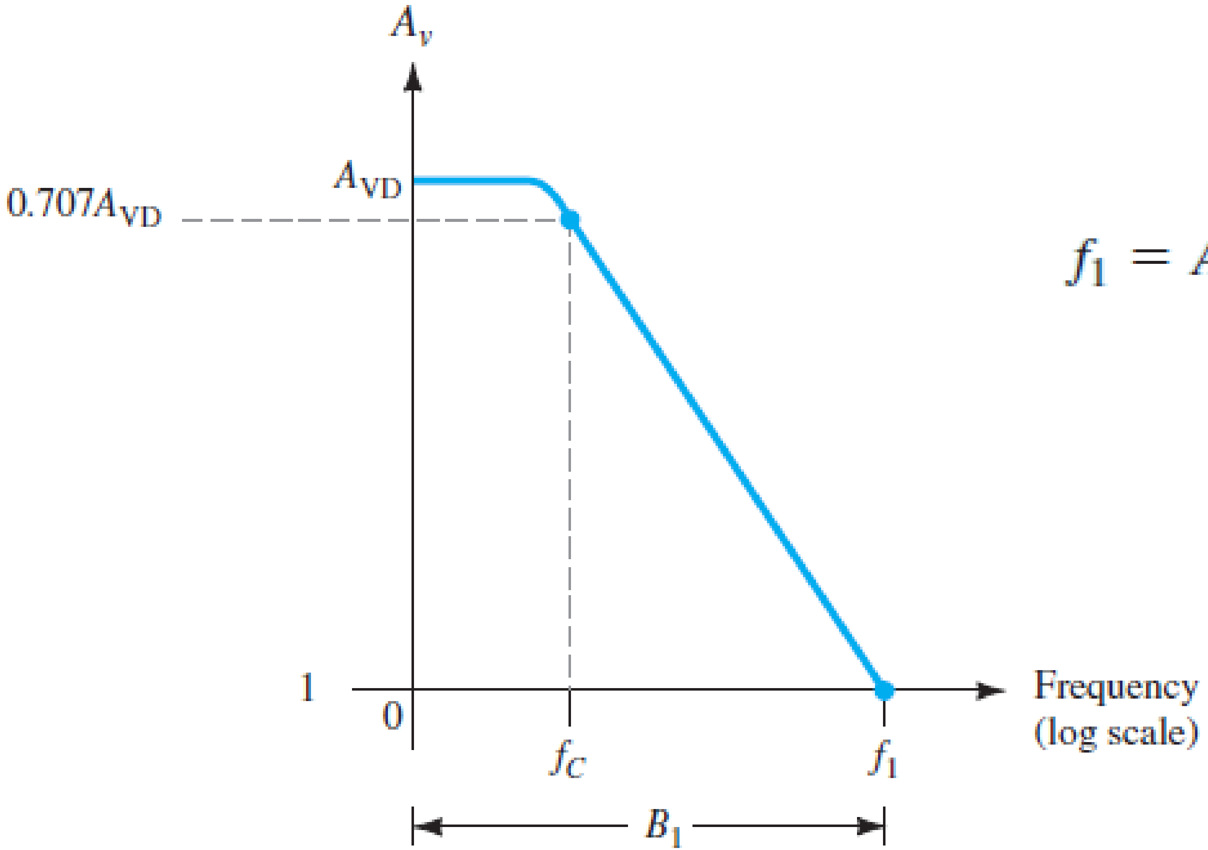
Block Diagram





A component-level diagram of the common 741 op amp.
Dotted lines outline:
current mirrors;
differential amplifier;
class A gain stage;
voltage level shifter;
output stage.

Gain–Bandwidth



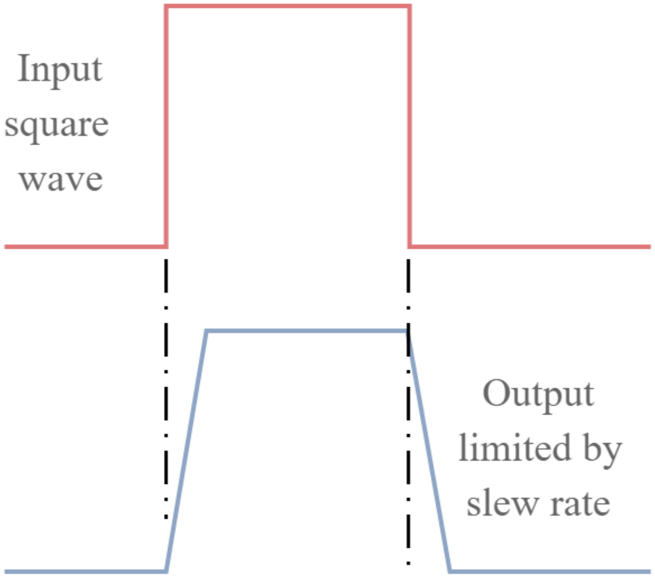
$$f_1 = A_{VD} f_C$$

Slew Rate (SR)

Slew rate = maximum rate at which amplifier output can change in volts per microsecond ($V/\mu s$)

Slew rate calculation & formula

$$\mathrm{SR} = \frac{\Delta V_o}{\Delta t}\ \mathrm{V}/\mu\mathrm{s} \quad \text{or} \quad SR = 2\pi f V$$



Where

Slew Rate (SR) is measured in volts / second, although actual measurements are often given in v/µs

f – the highest signal frequency, Hz

V – the maximum peak voltage of the signal.

Maximum Signal Frequency

The maximum frequency at which an op-amp may operate depends on both the bandwidth (BW) and slew rate (SR) parameters of the op-amp. For a sinusoidal signal of general form

$$v_o = K \sin(2\pi f t)$$

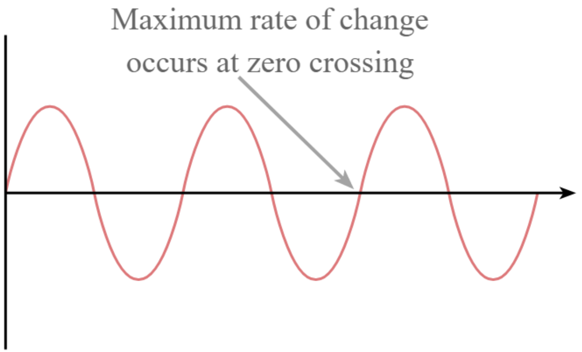
the maximum voltage rate of change can be shown to be

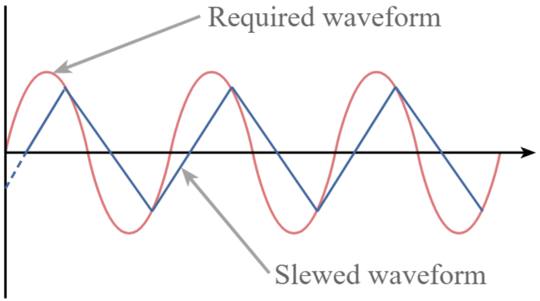
$$\text{signal maximum rate of change} = 2\pi f K \text{ V/s}$$

To prevent distortion at the output, the rate of change must also be less than the slew rate, that is,

$$2\pi f K \le \text{SR}$$
$$\omega K \le \text{SR}$$

$$\boxed{f \le \frac{\text{SR}}{2\pi K} \quad \text{Hz} \qquad \omega \le \frac{\text{SR}}{K} \quad \text{rad/s}}$$





Differential and common-mode operation

Differential Inputs $$V_d = V_{i_1} - V_{i_2}$$

Common Inputs $$V_c = \frac{1}{2}(V_{i_1} + V_{i_2})$$

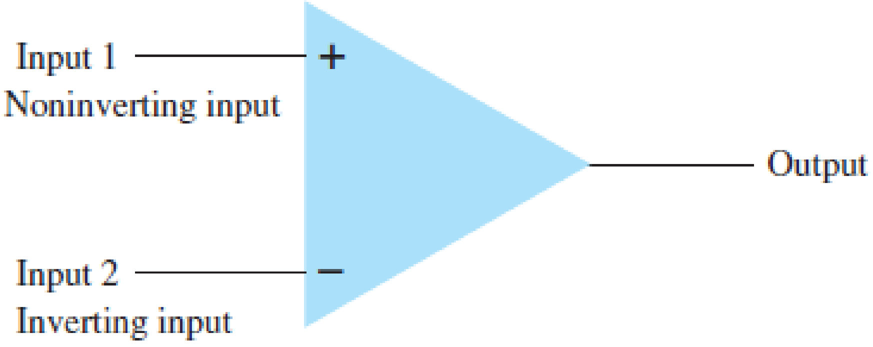
Output Voltage $$V_o = A_d V_d + A_c V_c$$

Common-Mode Rejection Ratio $$\mathrm{CMRR} = \frac{A_d}{A_c}$$

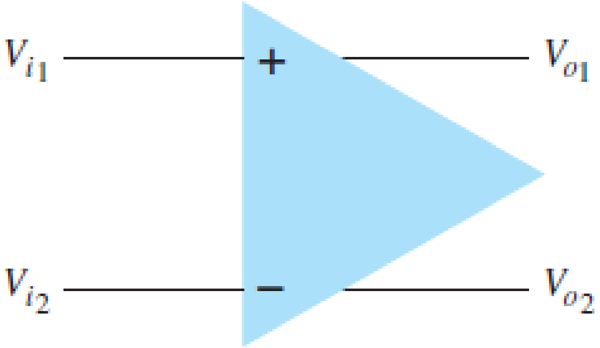
Single-Ended Input

- ✓ Single-Ended Input
- ✓ Double-Ended (Differential) Input
- ✓ Double-Ended Output
- ✓ Common-Mode Operation

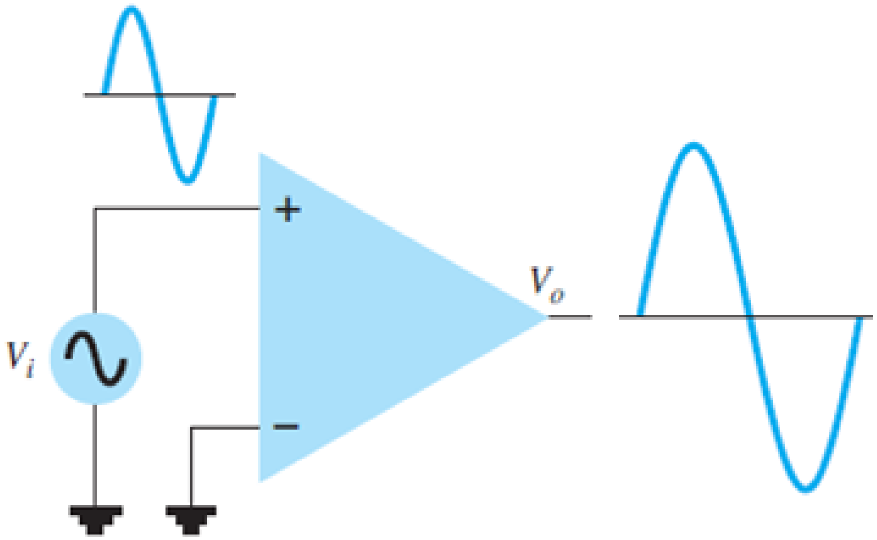
Double-ended input, Single-Ended output

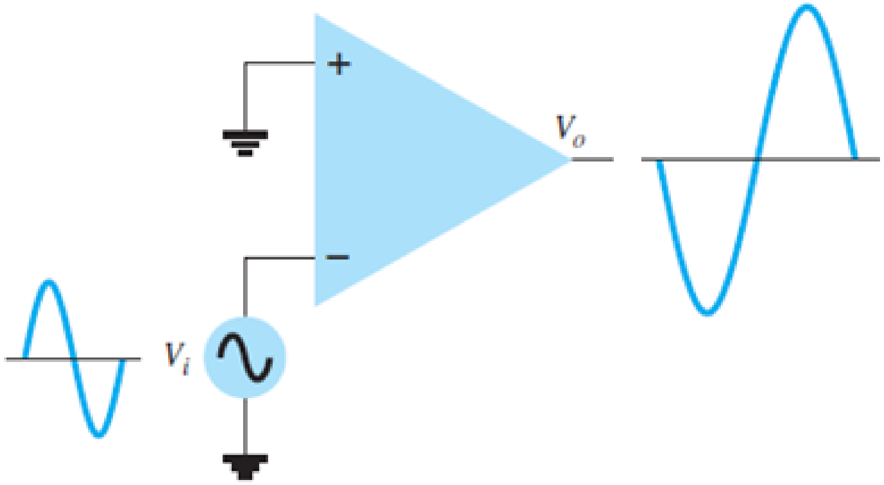


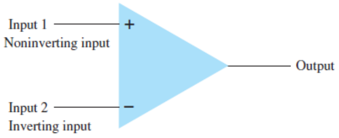
Double-ended input, double-ended output



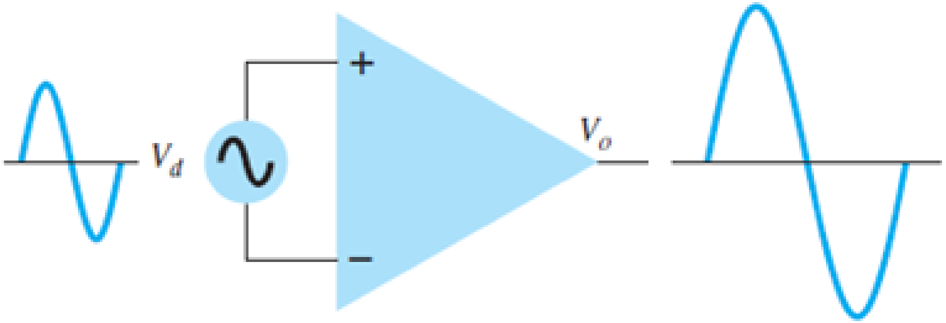
Single-Ended Input

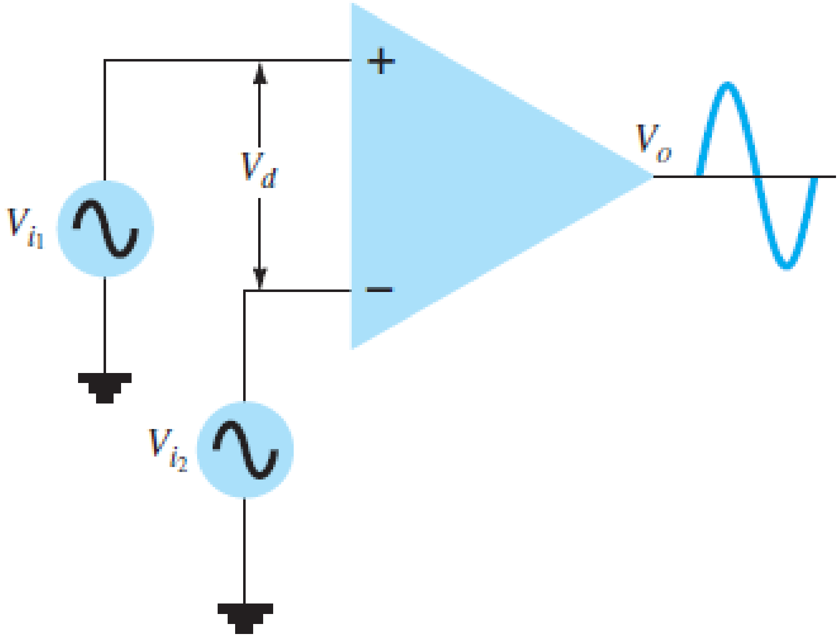


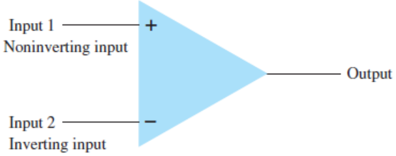




Double-Ended (Differential) Input

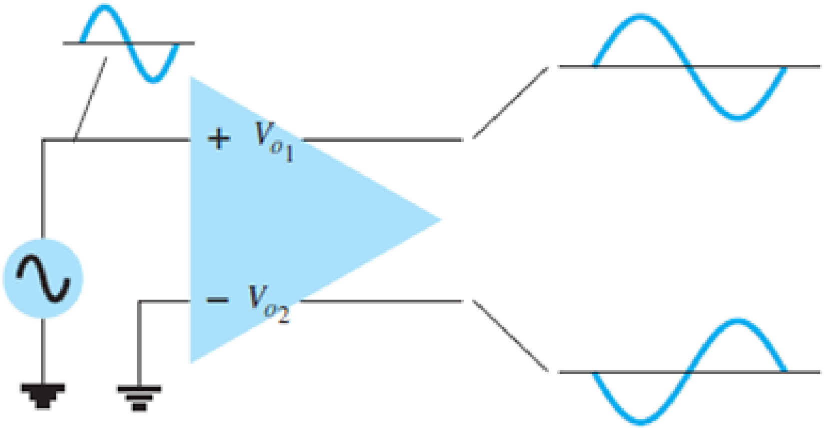




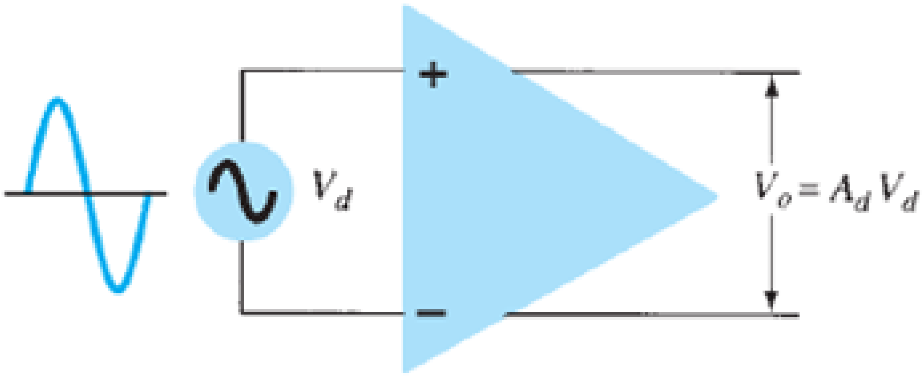


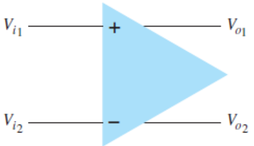
Double-Ended Output

Single-ended input with double-ended output



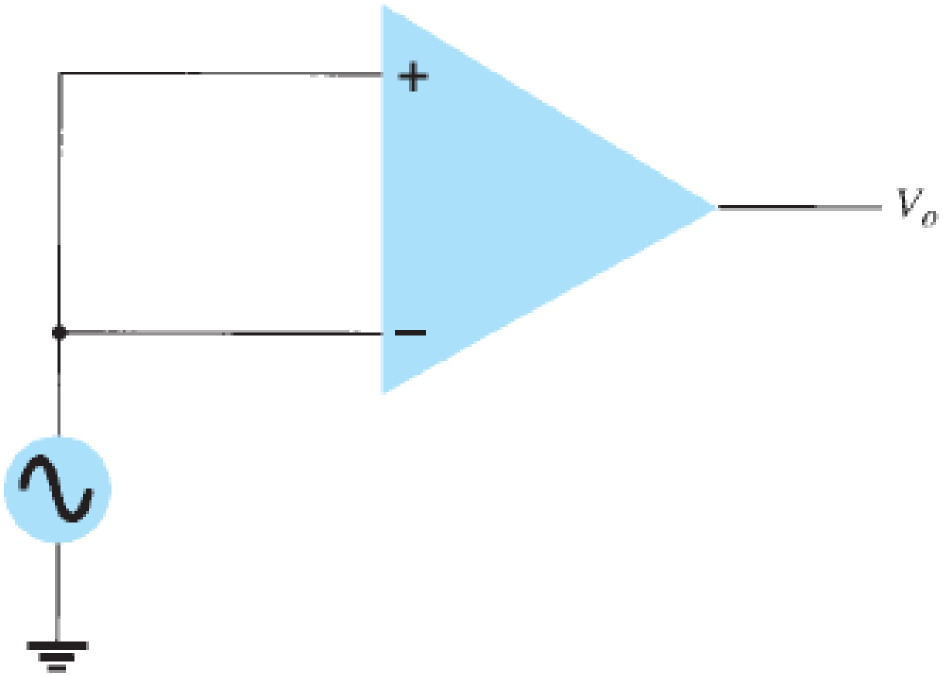
Differential-input, differential-output operation





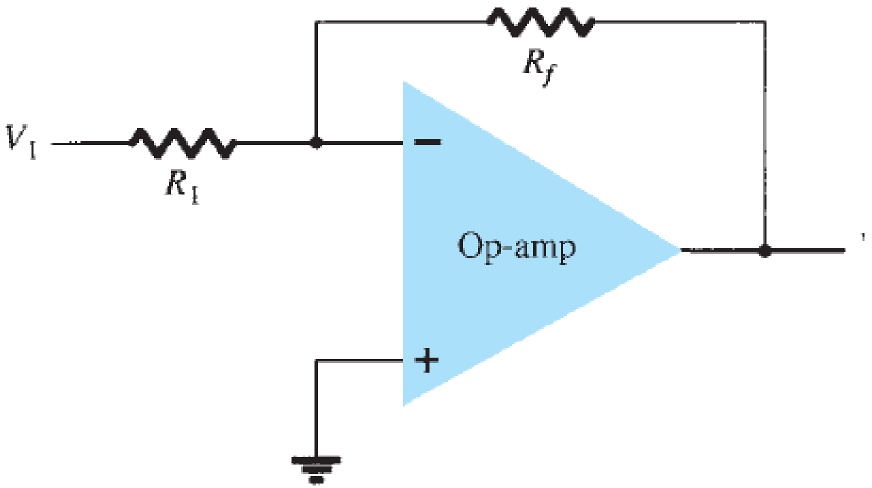
$$V_o = A_d V_d = V_{o1} - V_{o2}$$

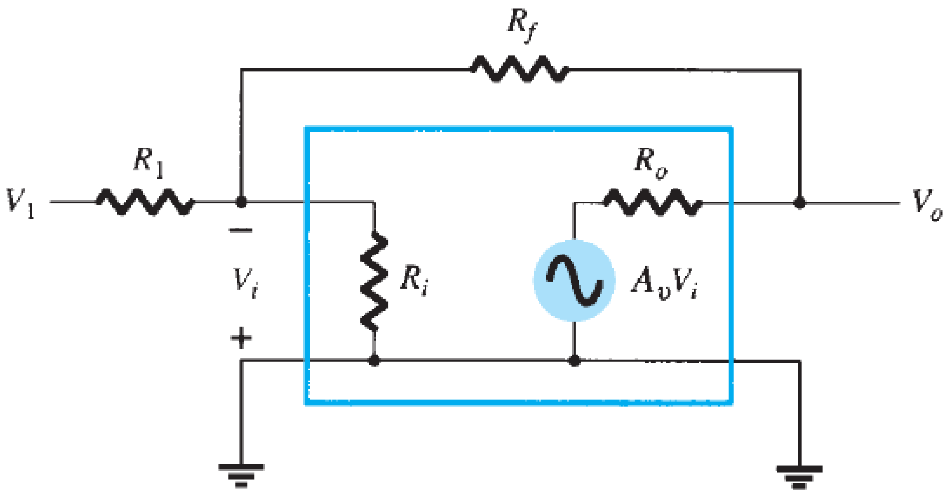
Common-Mode Operation



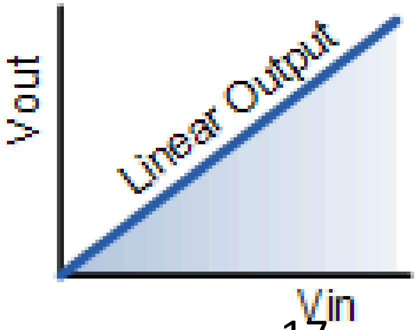
Single stage amplifier

Inverting Amplifier

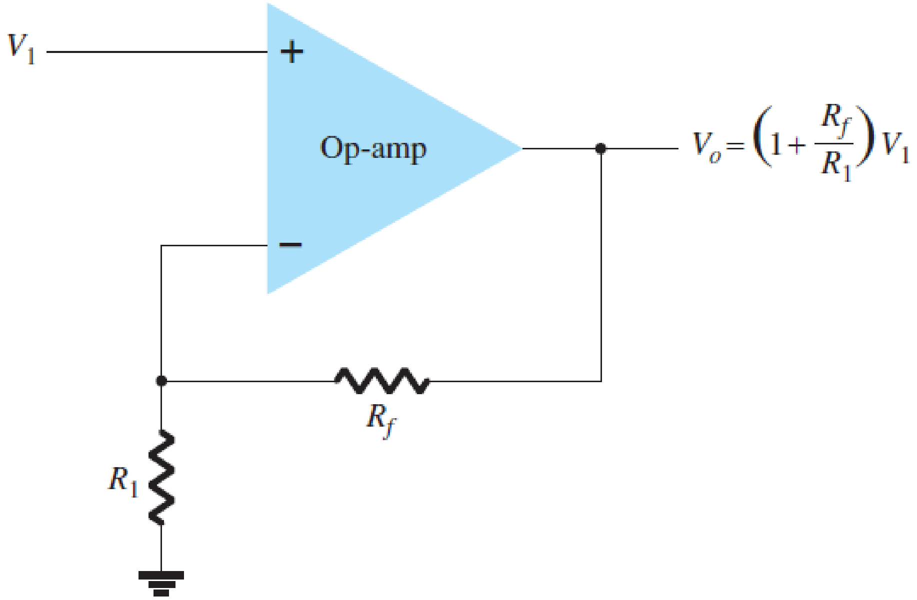


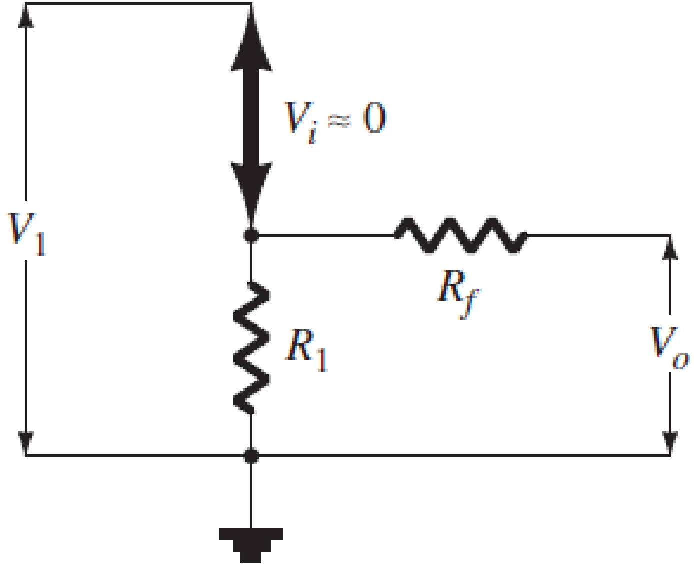


$$I_{R1} = I_{Rf} \Rightarrow V_o = -\frac{R_f}{R_1} V_i \Rightarrow \boxed{A_d = \frac{V_o}{V_i} = -\frac{R_f}{R_1}}$$



Noninverting Amplifier

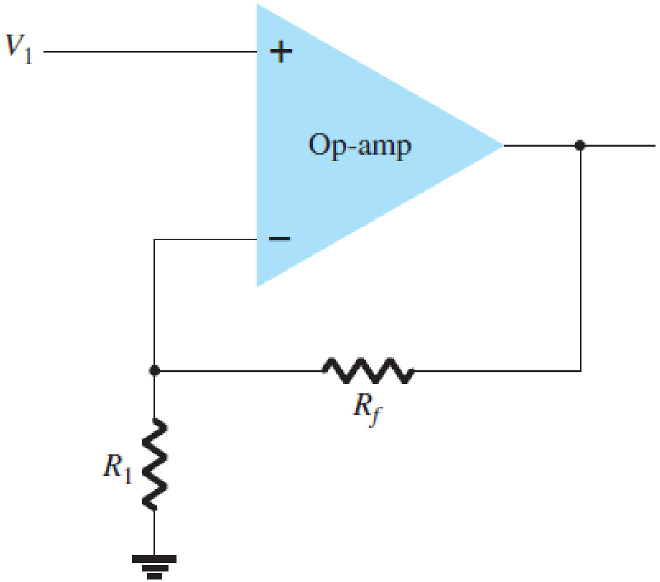


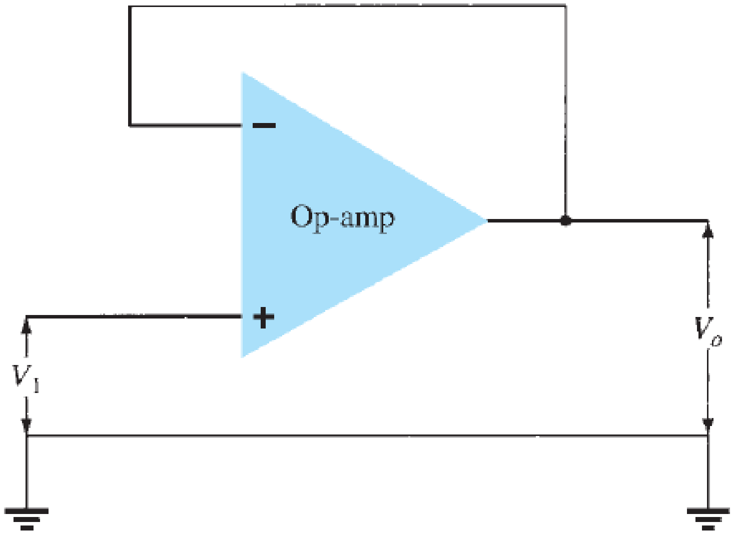


$$\frac{V_o}{V_1} = \frac{R_1 + R_f}{R_1} = 1 + \frac{R_f}{R_1}$$

Comparison Inverting And Noninverting Amplifier

Inverting Amplifier	Non-inverting Amplifier
The feedback used in amplifier is voltage shunt or negative feedback	The type of feedback used in amplifier is voltage series or negative feedback
The output of this amplifier is inverted	The output of is in phase by the input signal
the reference voltage can be given to the inverting terminal	In this amplifier, the reference voltage can be given to the non-inverting terminal
The gain is $A_d = -\frac{R_f}{R_1}$	The gain is $A_d = 1 + \frac{R_f}{R_1}$
The voltage gain is $A_d \leq\geq 1$ (less than, greater than or equal)	The voltage gain is $A_d \geq 1$
The input impedance is R_1	The input impedance is very large



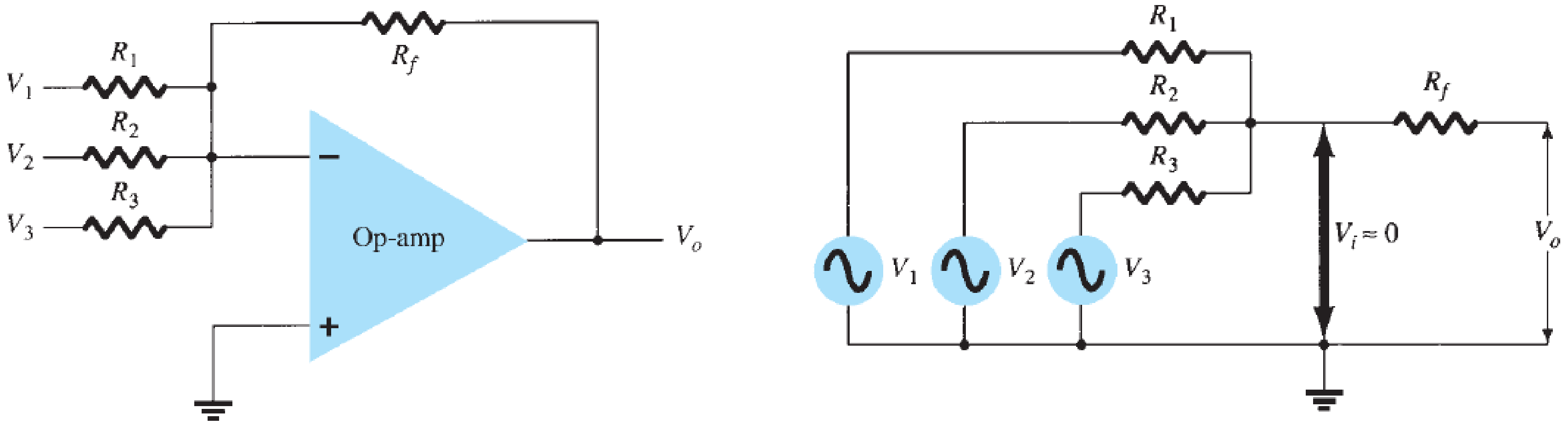


$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_1$$

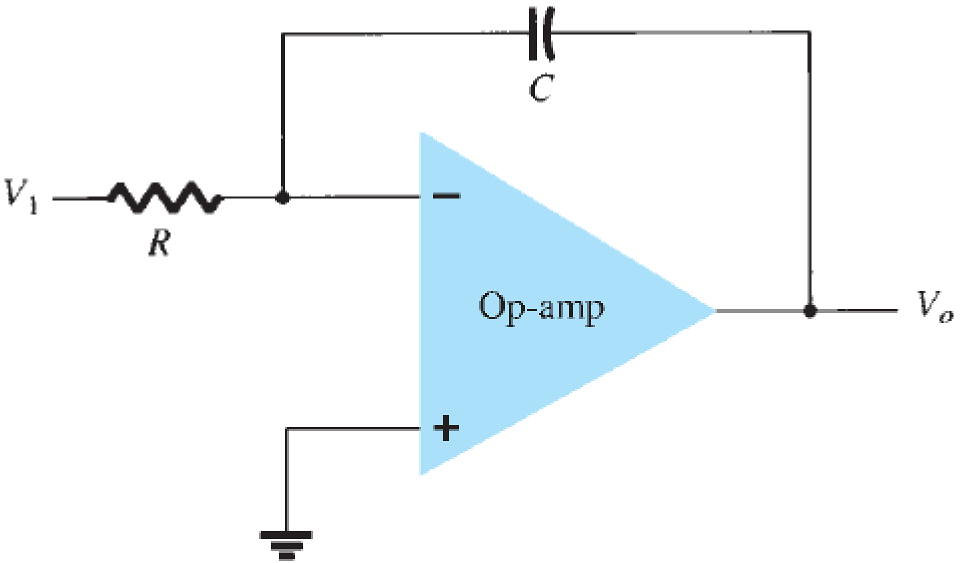
$$R_f \rightarrow 0$$
$$R_1 \rightarrow \infty$$

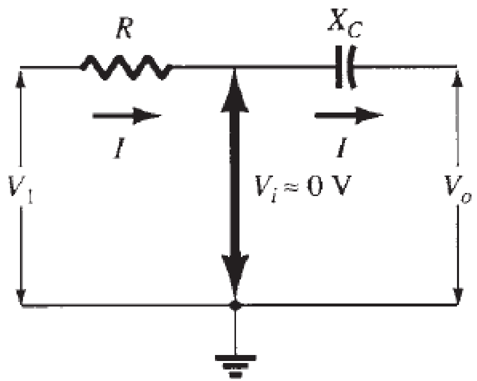
$$V_o = V_1$$

Summing Amplifier



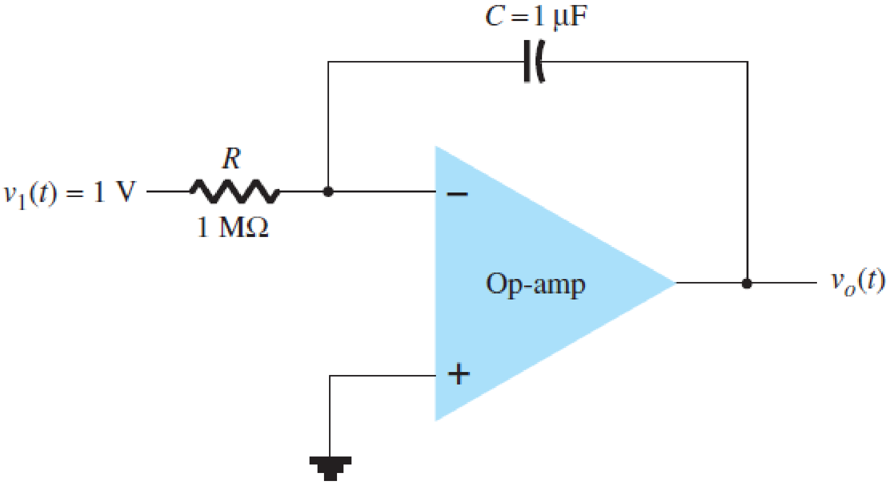
$$V_o = -\left(\frac{R_f}{R_1}V_1 + \frac{R_f}{R_2}V_2 + \frac{R_f}{R_3}V_3\right)$$





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

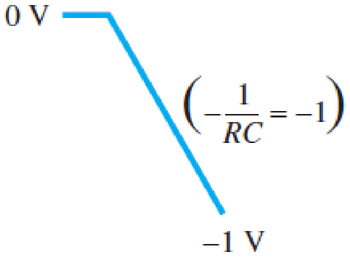
Integrator



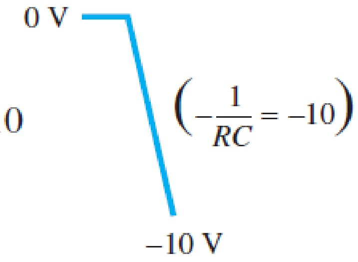
$$v_o(t) = -\frac{1}{RC}\int v_1(t)\,dt$$

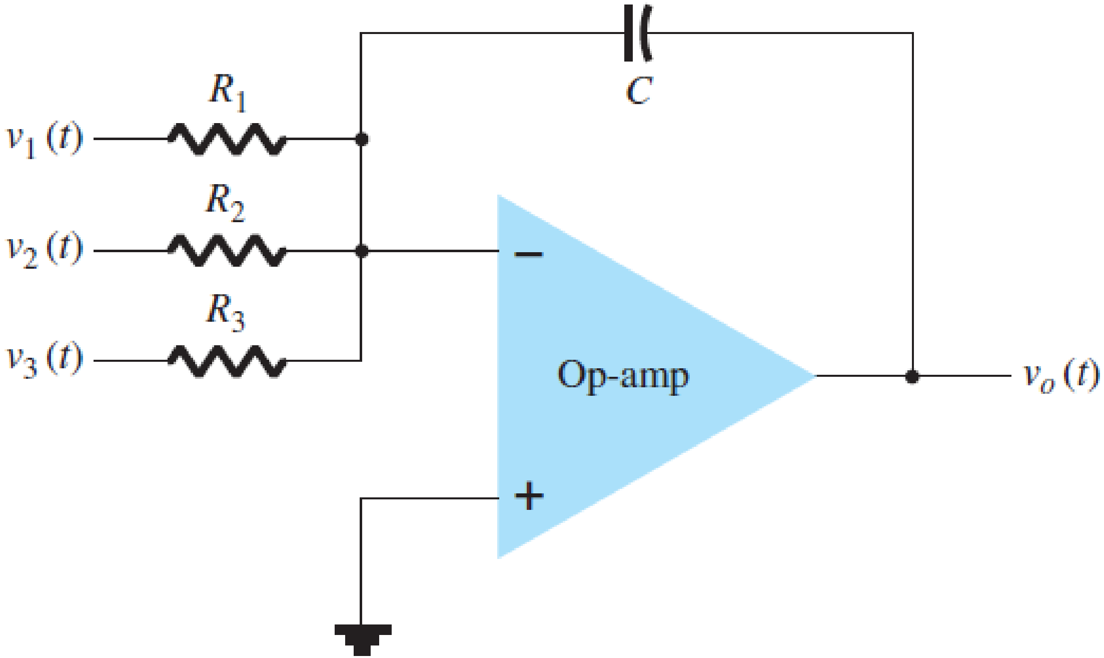
scale factor

$$-\frac{1}{RC} = \frac{1}{(1\ M\Omega)(1\ \mu F)} = -1$$



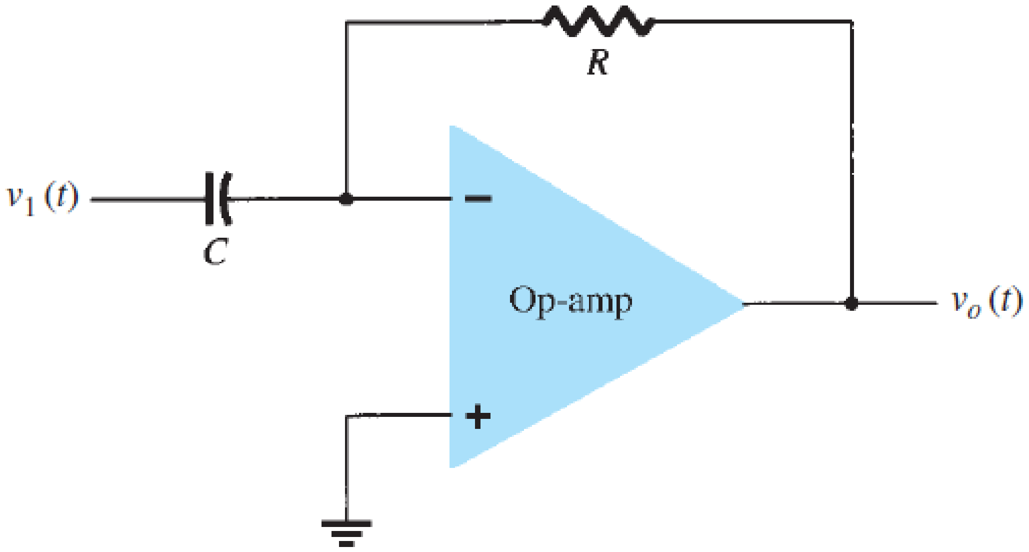
$$-\frac{1}{RC} = \frac{1}{(100\ k\Omega)(1\ \mu F)} = -10$$



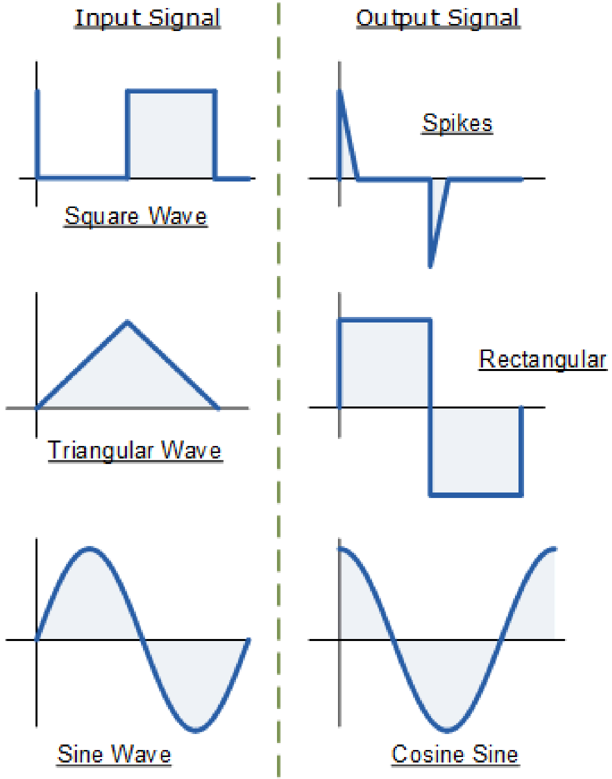


$$v_o(t) = -\left[\frac{1}{R_1C}\int v_1(t)\,dt + \frac{1}{R_2C}\int v_2(t)\,dt + \frac{1}{R_3C}\int v_3(t)\,dt\right]$$

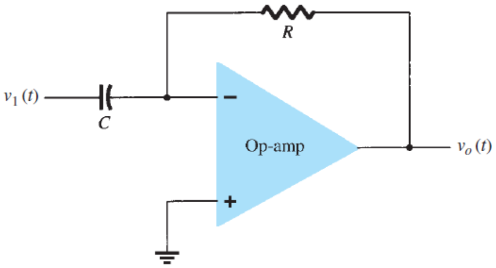
Differentiator



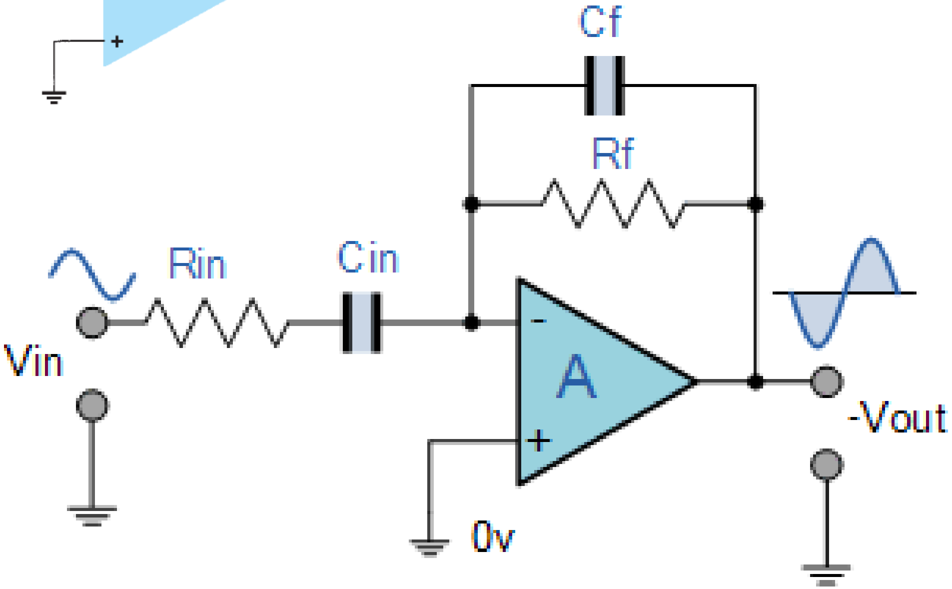
$$v_o(t) = -RC\frac{dv_1(t)}{dt}$$



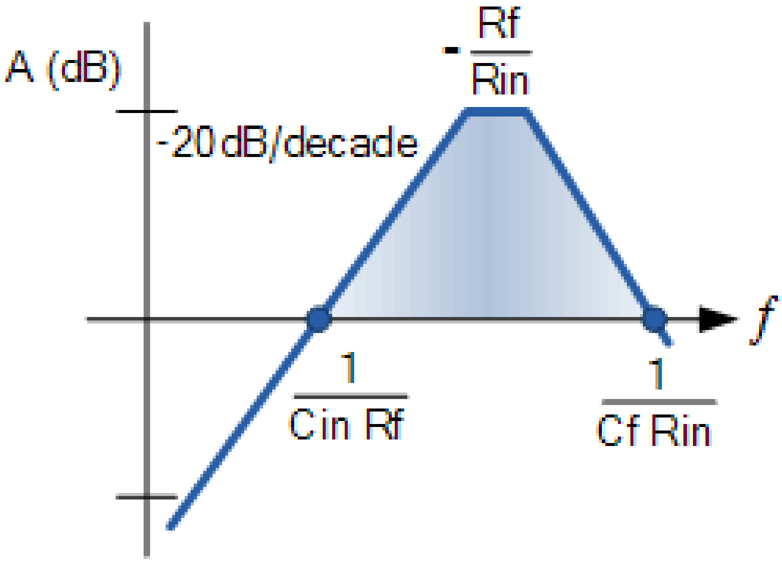
Integrator



R
$v_1(t)$
C
Op-amp
$v_o(t)$



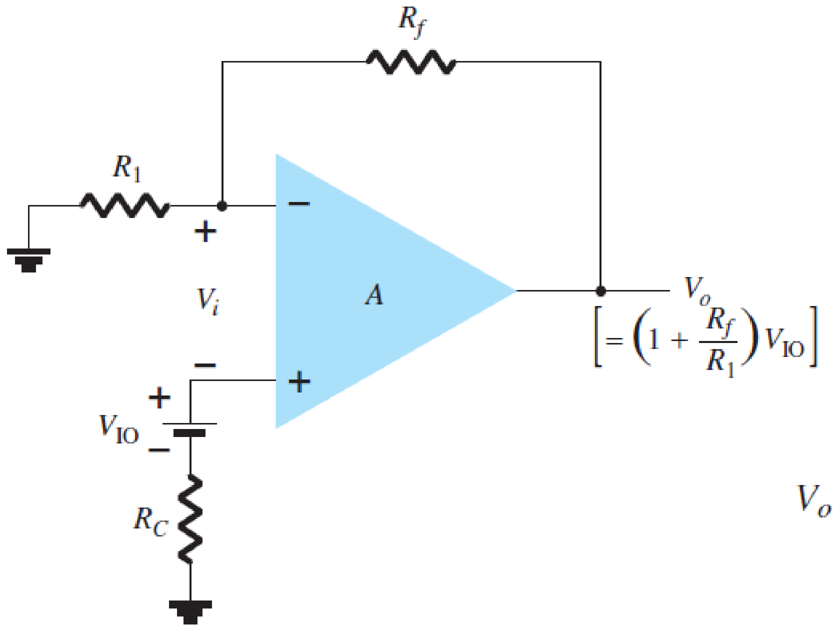
Cf
Rf
Rin
Cin
Vin
A
-Vout
0v



A (dB)
-20dB/decade
- Rf/Rin
1/(Cin Rf)
1/(Cf Rin)
f

Offset Currents and Voltages in OP Amp

Input Offset Voltage



$$V_o = A * V_i$$

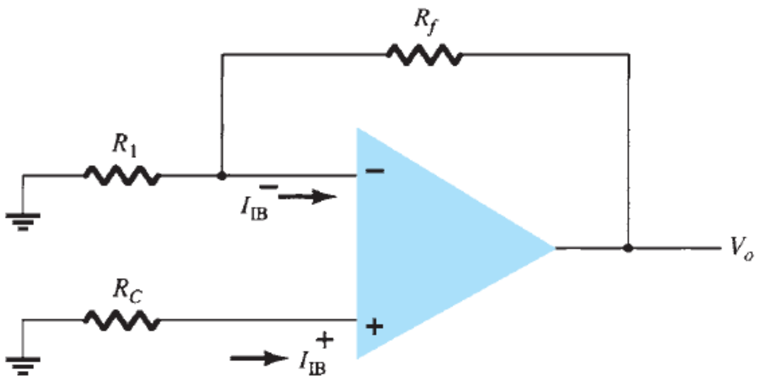
$$V_o = AV_i = A\left(V_{IO} - V_o\frac{R_1}{R_1 + R_f}\right)$$

Solving for V_o

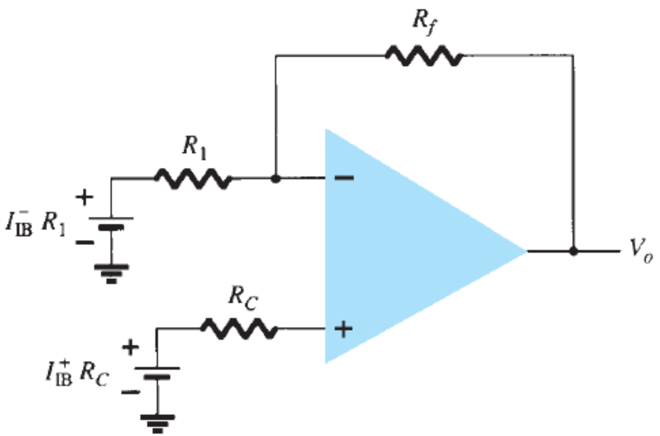
$$V_o = V_{IO}\frac{A}{1 + A\left[R_1/(R_1 + R_f)\right]} \approx V_{IO}\frac{A}{A\left[R_1/(R_1 + R_f)\right]}$$

$$V_o(\text{offset}) = V_{IO}\frac{R_1 + R_f}{R_1}$$

Input Offset Current



$$I_{IO} = I_{IB}^+ - I_{IB}^-$$



$$V_o^+ = I_{IB}^+ R_C\left(1 + \frac{R_f}{R_1}\right)$$

$$V_o(\text{offset due to } I_{IB}^+ \text{ and } I_{IB}^-) = I_{IB}^+ R_C\left(1 + \frac{R_f}{R_1}\right) - I_{IB}^- R_1\frac{R_f}{R_1}$$

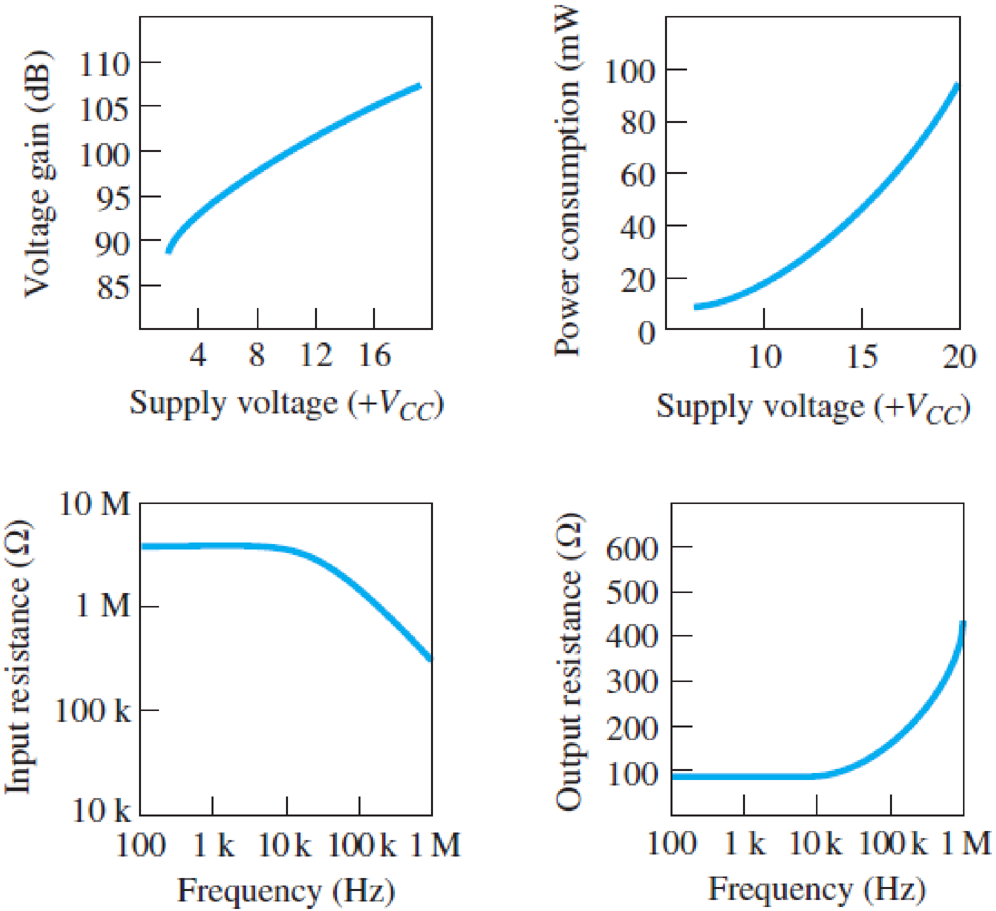
$$V_o^- = I_{IB}^- R_1\left(-\frac{R_f}{R_1}\right)$$

$$V_o(\text{offset due to } I_{IO}) = I_{IO} R_f$$

Total Offset Due to Offset Voltage and Current

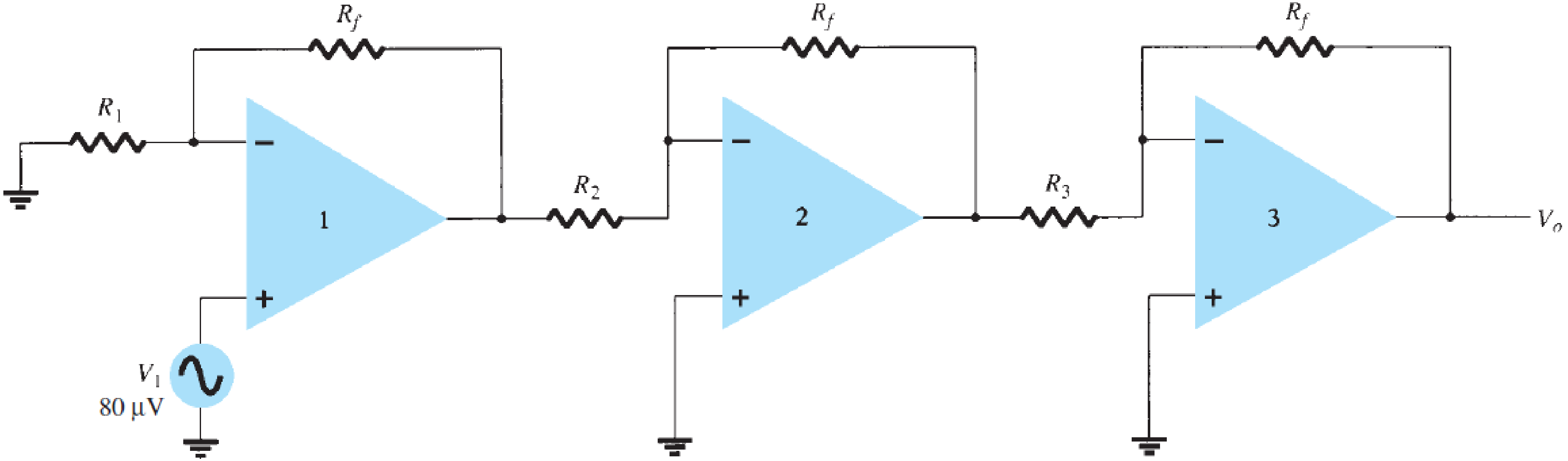
$$\left|V_o(\text{offset})\right| = \left|V_o(\text{offset due to} V_{\text{IO}})\right| + \left|V_o(\text{offset due to } I_{\text{IO}})\right|$$

Op-Amp Performance



Multiple-Stage amplifier

Multiple-Stage Gains



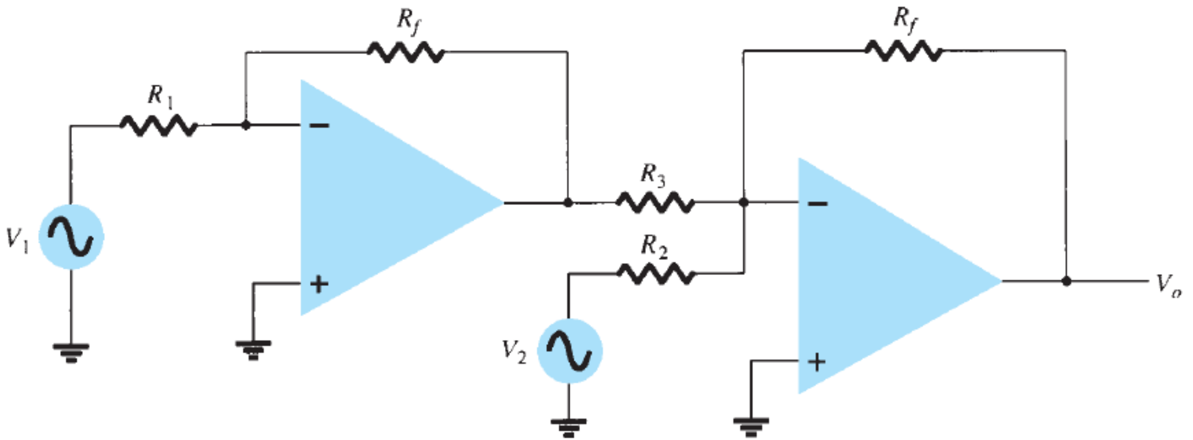
$$A_1 = 1 + \frac{R_f}{R_1}$$

$$A_2 = -\frac{R_f}{R_2}$$

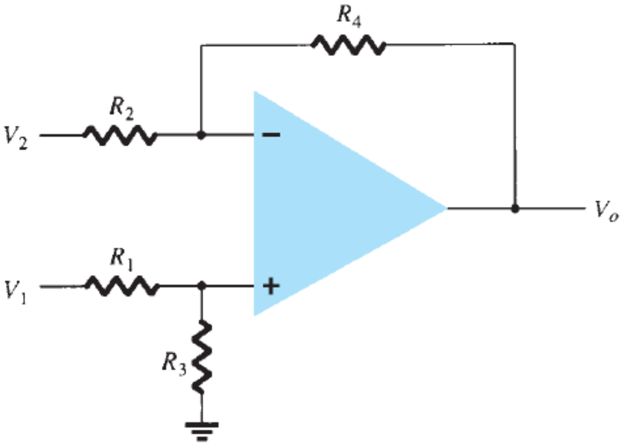
$$A_3 = -\frac{R_f}{R_3}$$

$$A = A_1 A_2 A_3$$

Voltage Subtraction

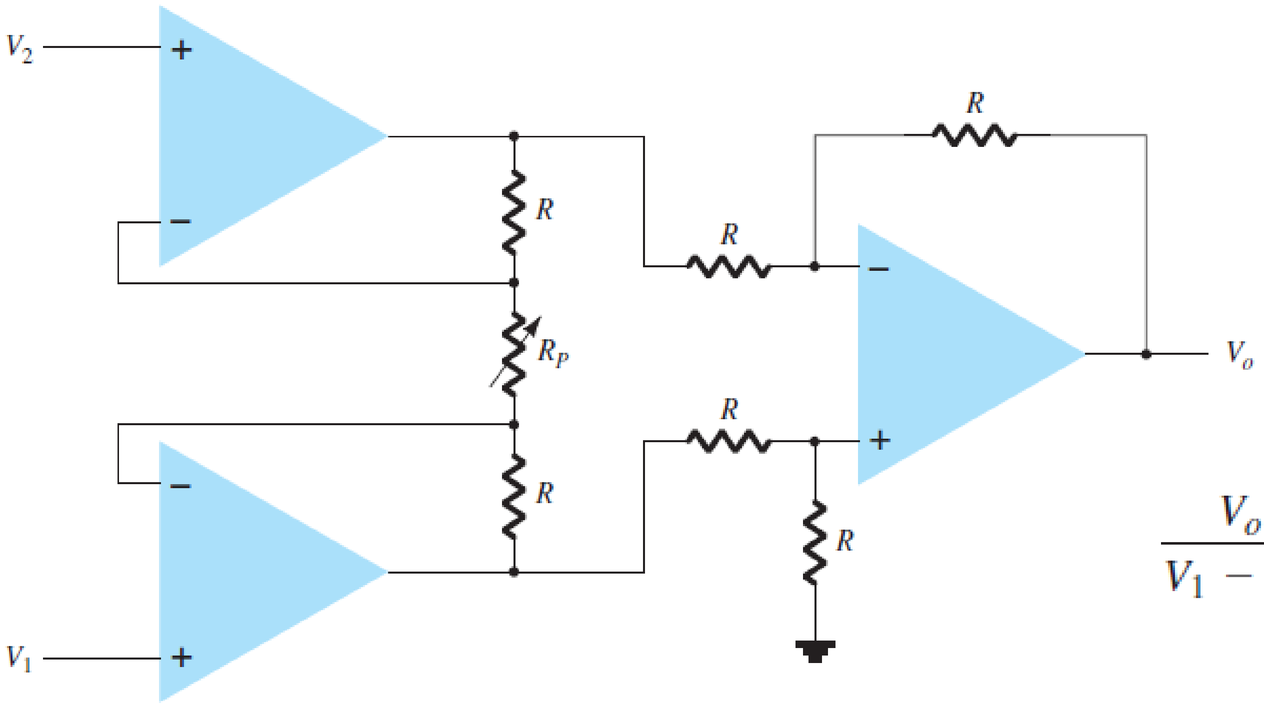


$$V_o = -\left(\frac{R_f}{R_2}V_2 - \frac{R_f}{R_3}\frac{R_f}{R_1}V_1\right)$$



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

Instrumentation Amplifier

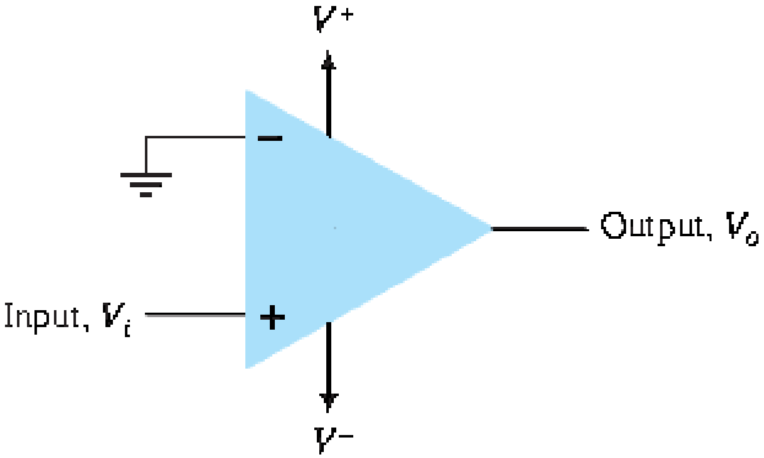


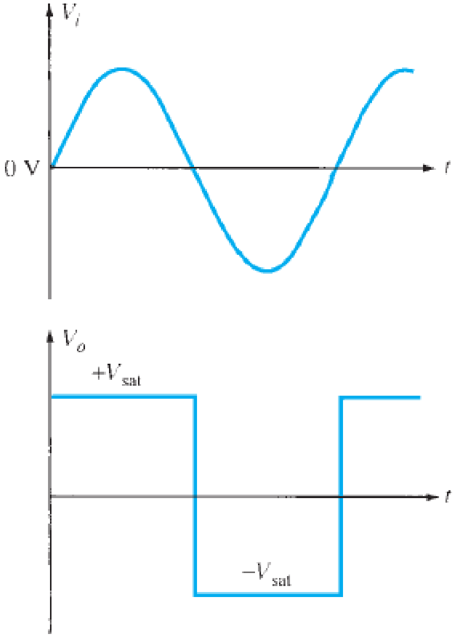
$$\frac{V_o}{V_1 - V_2} = 1 + \frac{2R}{R_P}$$

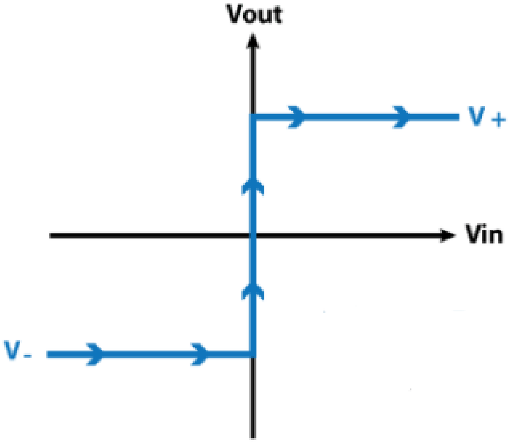
$$V_o = \left(1 + \frac{2R}{R_P}\right)(V_1 - V_2) = k(V_1 - V_2)$$

Nonlinear Circuits

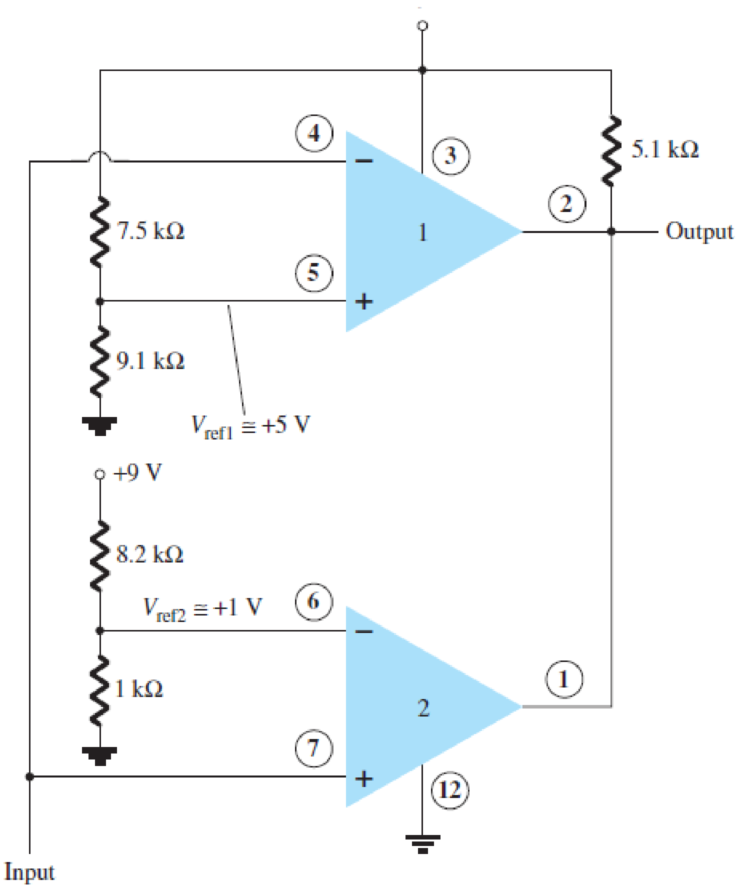
Comparator

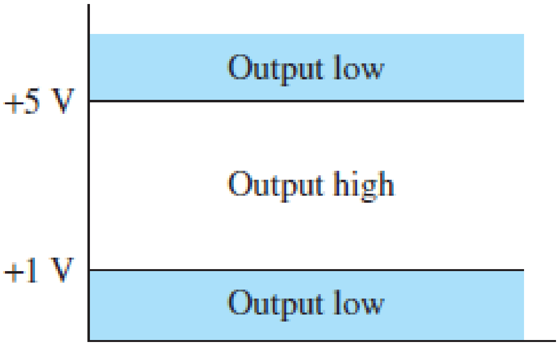




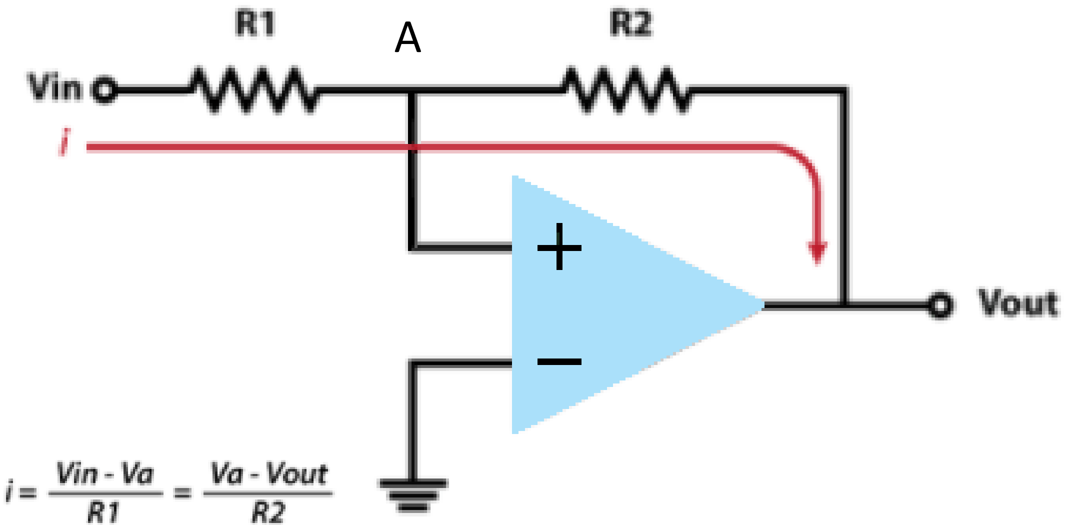


Comparator


4
3
5.1 kΩ
2
1
Output
7.5 kΩ
5
9.1 kΩ
$V_{ref1} \cong +5$ V
+9 V
8.2 kΩ
$V_{ref2} \cong +1$ V
6
1 kΩ
2
1
7
12
Input


Output low
+5 V
Output high
+1 V
Output low

Schmitt trigger

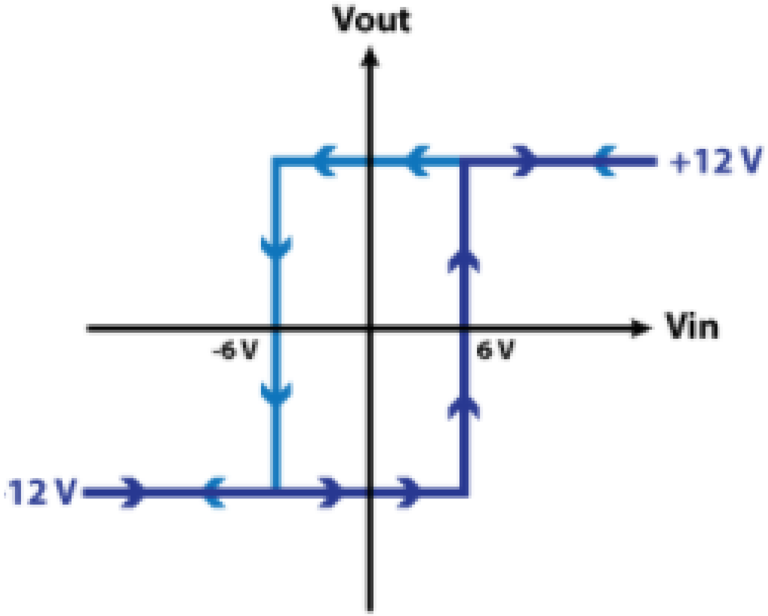


$$i = \frac{Vin - Va}{R1} = \frac{Va - Vout}{R2}$$

$$Va = 0$$

$$\frac{Vin}{R1} = -\frac{Vout}{R2}$$

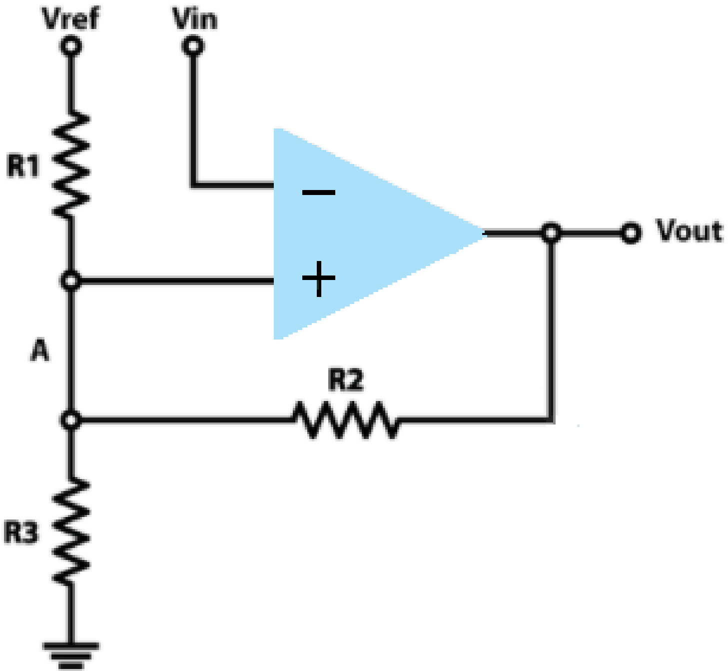
$$V_{in} = -\frac{R_1}{R_2} V_{out}$$



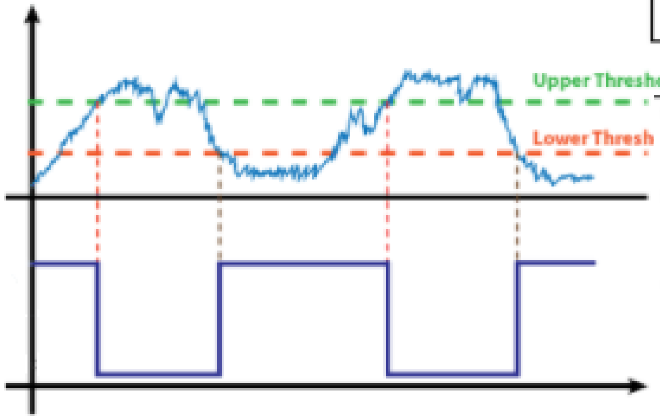
Example:
R1 = 1K ; R2 = 2K ; Vout = +/- 12 V

$$Vin = -\frac{1}{2}(+/-12) = +/-6\ V$$

Non-Symmetrical Schmitt Trigger



Example:
R1, R2, R3 = 10K ; Vref = 5 V



Inverted Output

Vout = 0 V

$$Va = \frac{R2 \,||\, R3}{R1 + R2 \,||\, R3} Vref$$

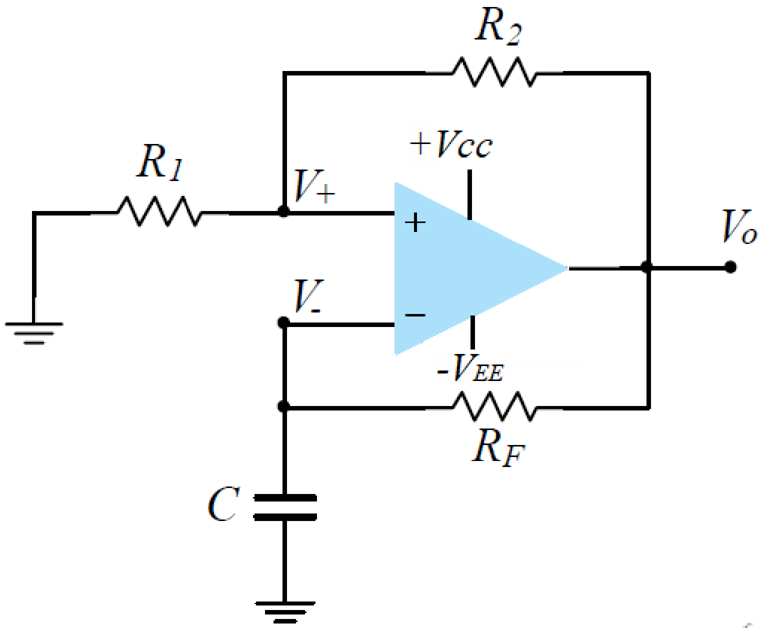
$Va = 1{,}66\ V$

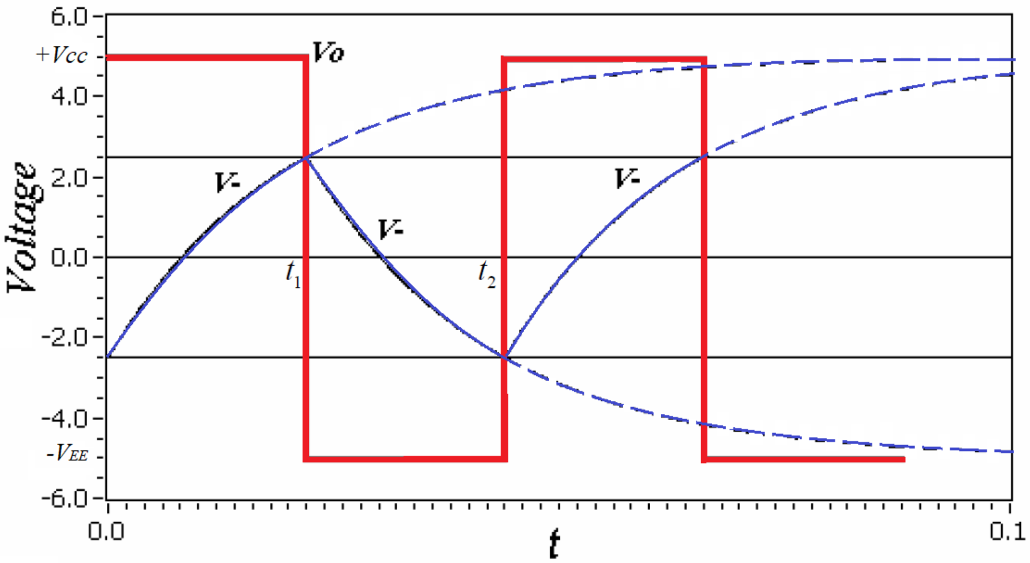
Vout = 5 V

$$Va = \frac{R2}{R2 + R1 \,||\, R3} Vref$$

$Va = 3{,}33\ V$

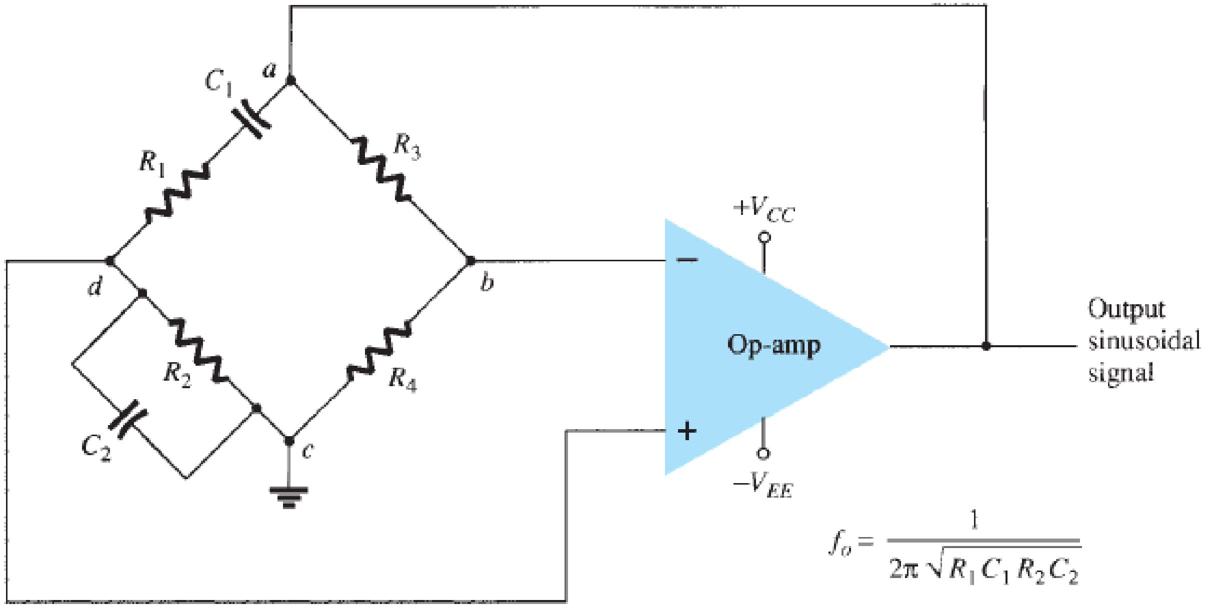
Multivibrator





$$T = 2R_F C \ln\left(1 + 2\frac{R1}{R2}\right)$$

Wien Bridge Oscillator



$$\frac{R_3}{R_4} = \frac{R_1}{R_2} + \frac{C_2}{C_1}$$

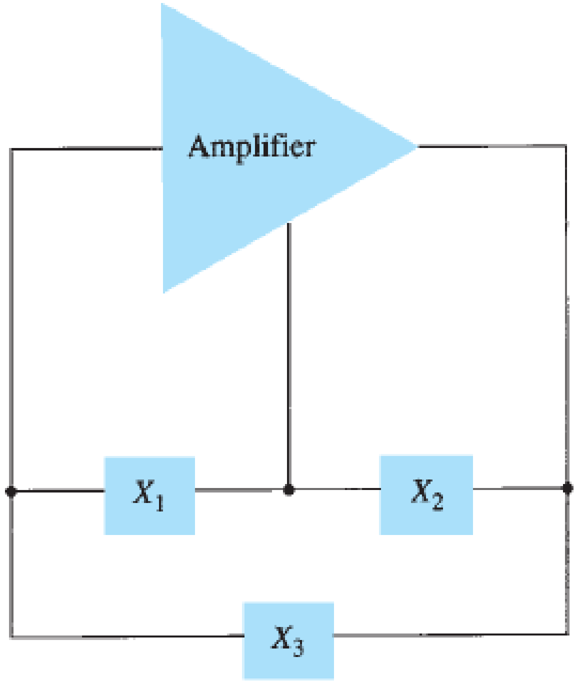
$$f_o = \frac{1}{2\pi\sqrt{R_1 C_1 R_2 C_2}}$$

If, in particular, the values are $R_1 = R_2 = R$ and $C_1 = C_2 = C$, the resulting oscillator frequency is

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

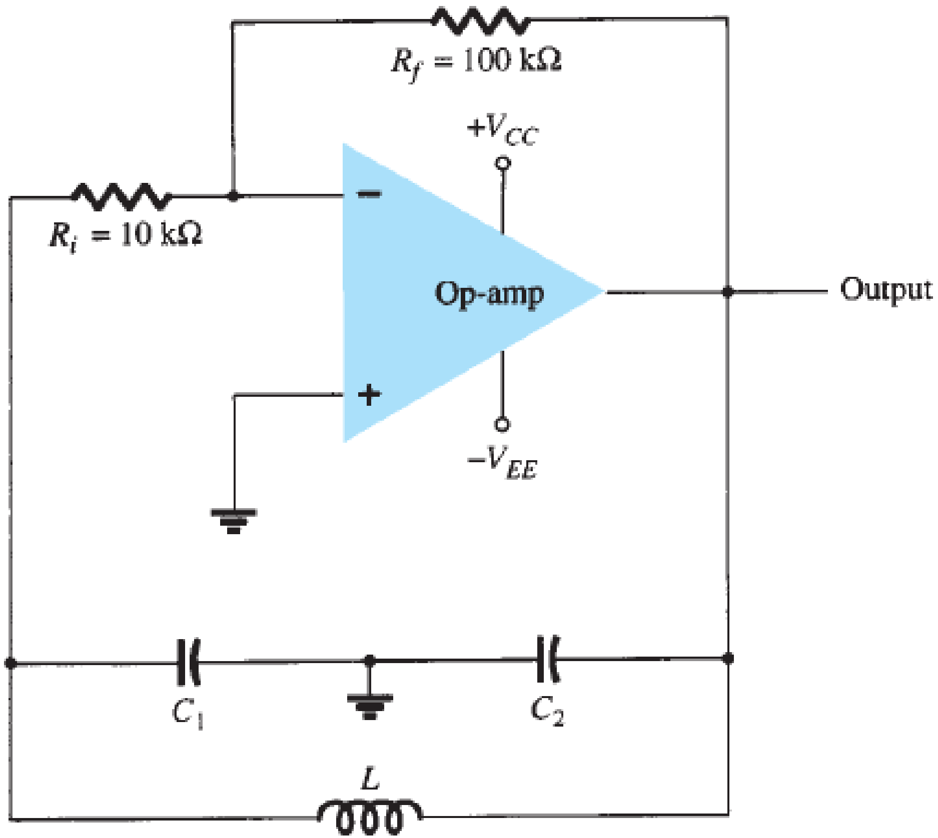
$$\frac{R_3}{R_4} = 2$$

Tuned Oscillator Circuit



Oscillator Type	Reactance Element X_1	X_2	X_3
Colpitts oscillator	C	C	L
Hartley oscillator	L	L	C
Tuned input, tuned output	LC	LC	—

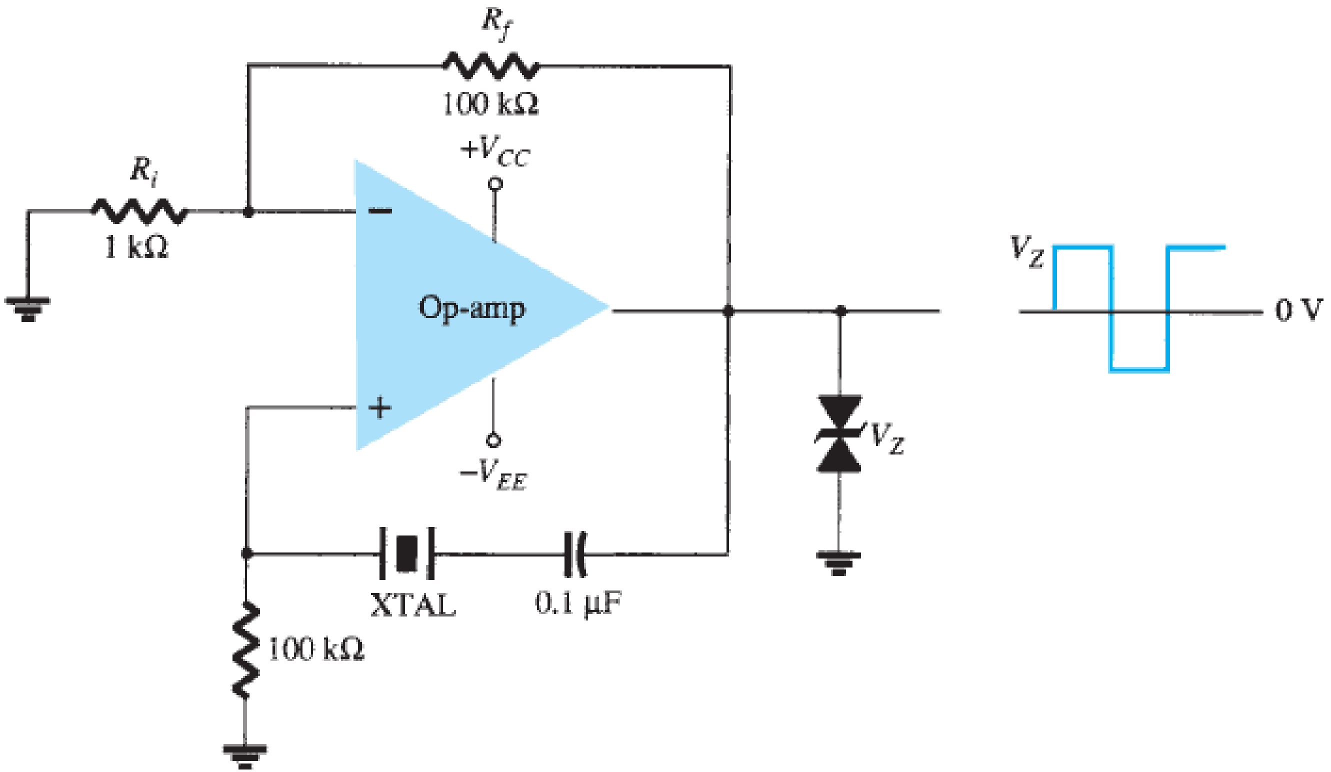
Colpitts oscillator



$$f_o = \frac{1}{2\pi\sqrt{LC_{\text{eq}}}}$$

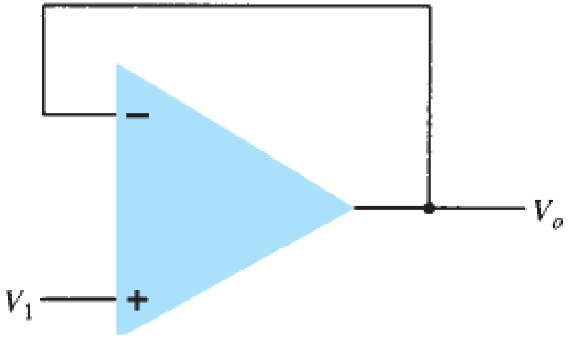
$$C_{\text{eq}} = \frac{C_1 C_2}{C_1 + C_2}$$

Crystal Oscillator

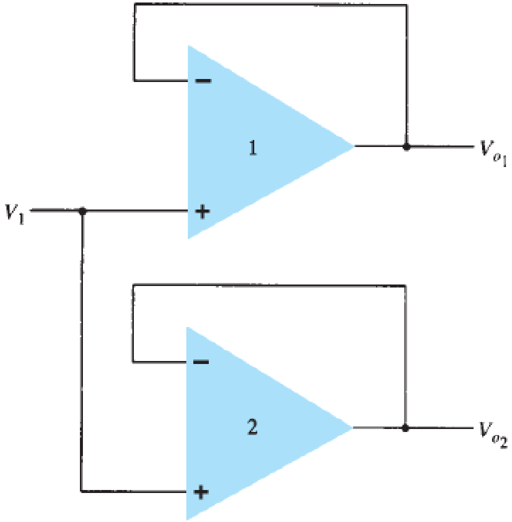


Controlled Voltage Source

Voltage buffer



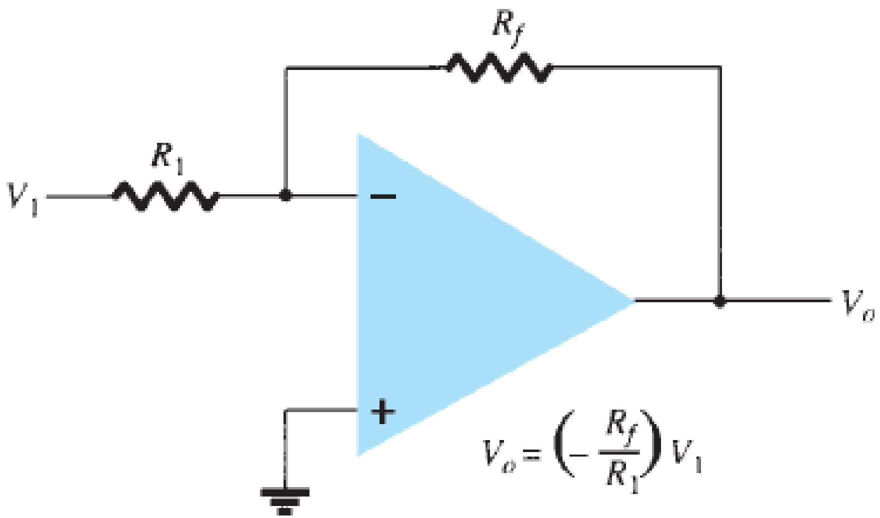
$$V_o = V_1$$

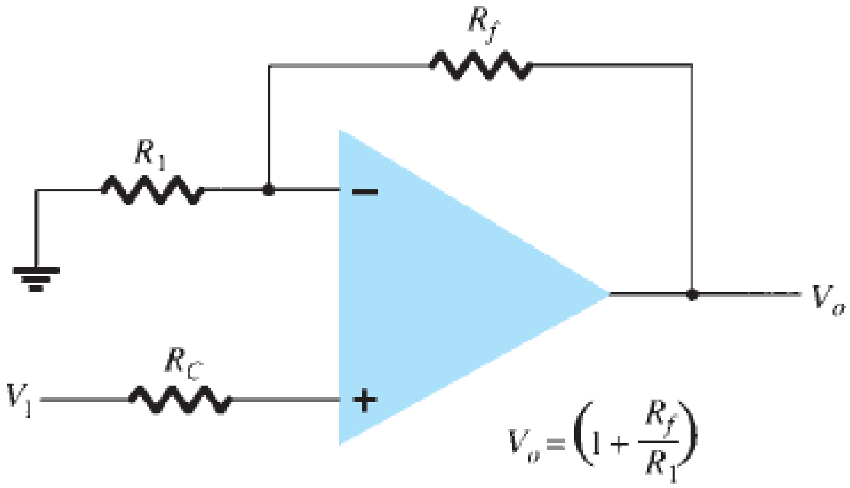


Advantages of Voltage Follower

1. Very large input resistance
2. Very low output resistance
3. Large bandwidth
4. The output follows the input exactly without any phase shift

Voltage-Controlled Voltage Source

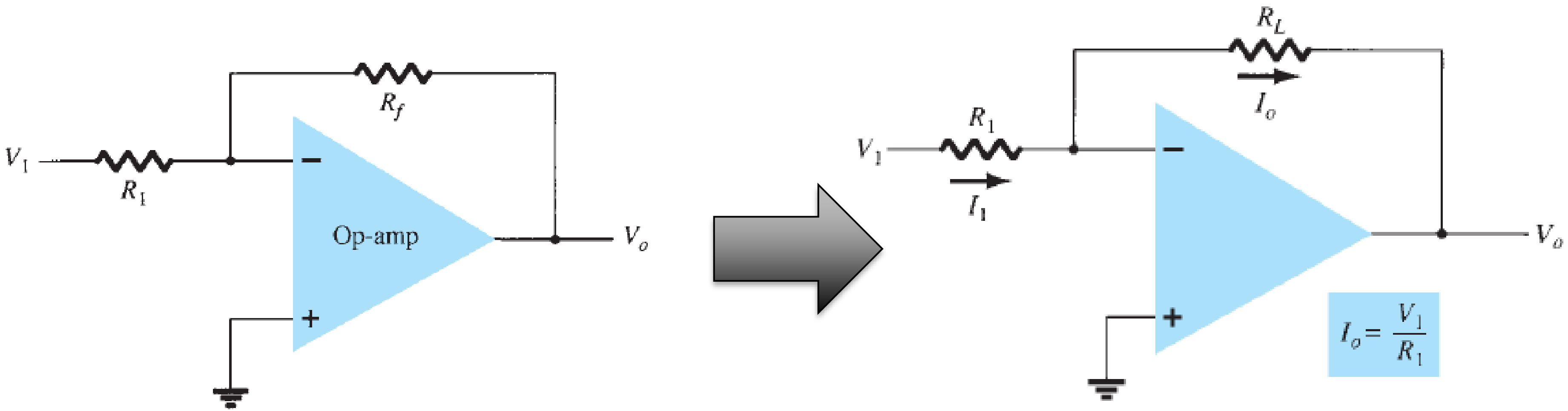




$$V_o = -\frac{R_f}{R_1} V_1 = k V_1$$

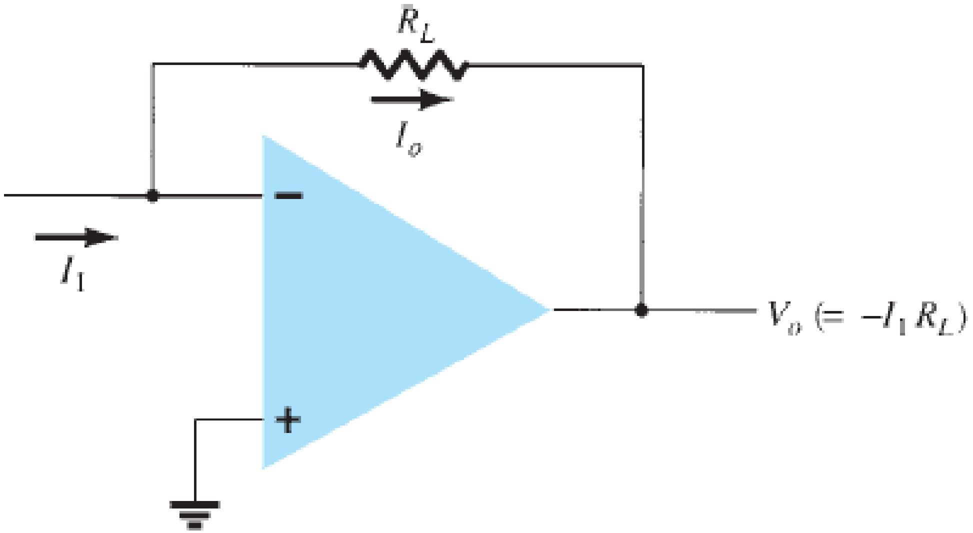
$$V_o = \left(1 + \frac{R_f}{R_1}\right) V_1 = k V_1$$

Voltage-Controlled Current Source



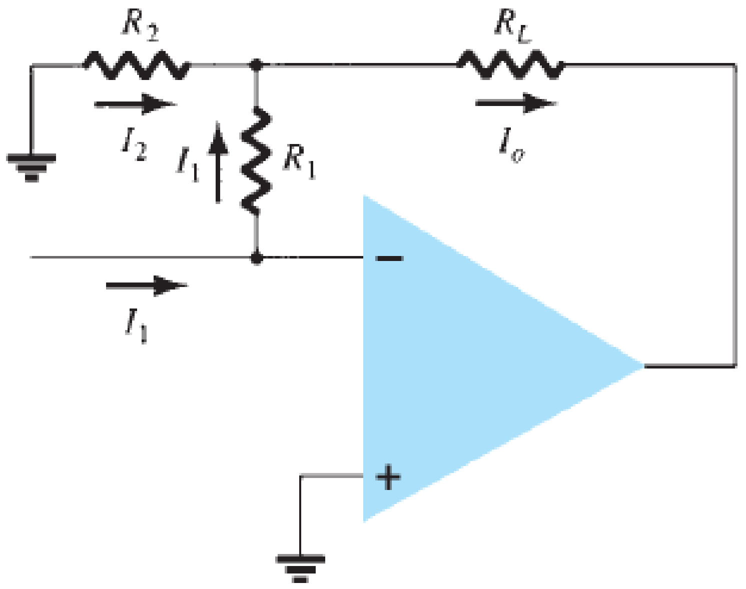
$$I_o = \frac{V_1}{R_1} = kV_1$$

Current-Controlled Voltage Source



$$V_o = -I_1 R_L = kI_1$$

Current-Controlled Current Source



$$I_o = I_1 + I_2 = I_1 + \frac{I_1 R_1}{R_2} = \left(1 + \frac{R_1}{R_2}\right) I_1 = kI_1$$

References

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Thank you for your attention!