Basic Electronics Engineering (Spring 2024)

Resources of PPT:

- www.google.com

- Digital Design, 4th Edition
  M. Morris Mano and Michael D. Ciletti

Analog Electronics

Reference Book:

1. **R. BOYLESTAD and L. NASHELSKY, "Electronic Devices And Circuit Theory", Prentice Hall.**
2. **Sedra and Smith, "Microelectronic Circuits", Oxford University Press**

OPAMP: Operational Amplifier

Basic characteristics:

- high gain differential amplifier
- high input impedance (ideally infinite Zin)
- low output impedance (ideally zero $Zout$)

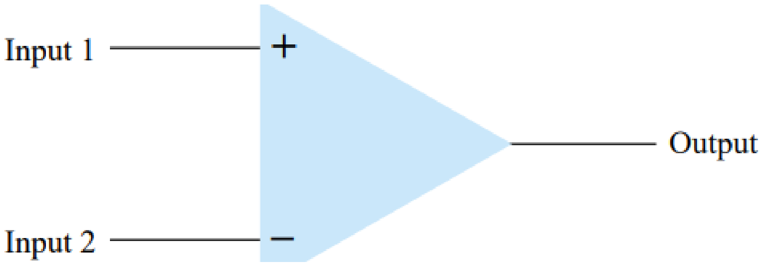


Fig: Basic op-amp.

Single-Ended OPAMP:

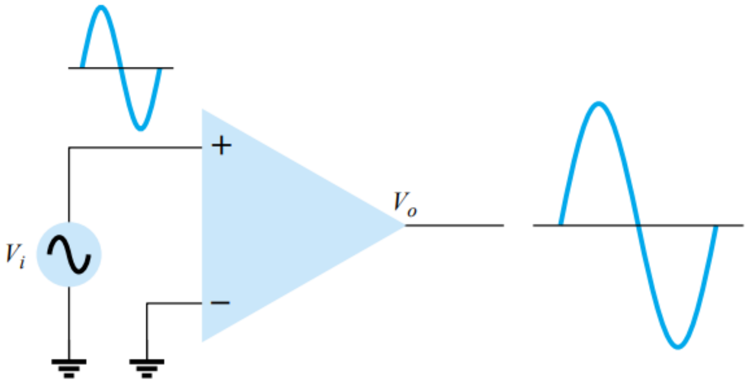


Fig: Input at non-inverting terminal.

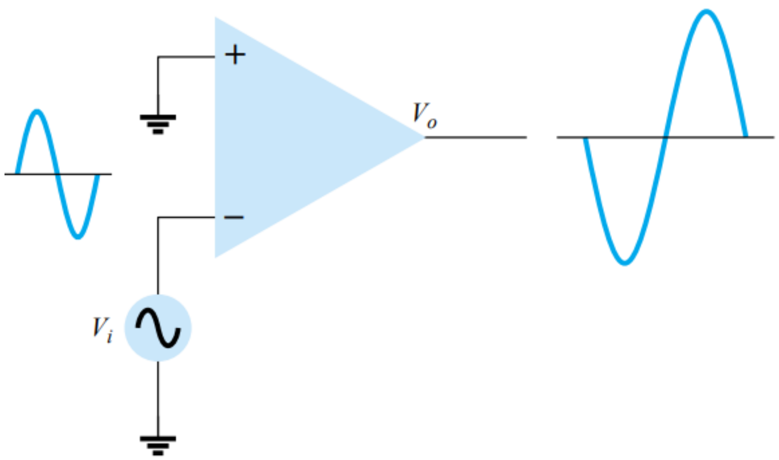
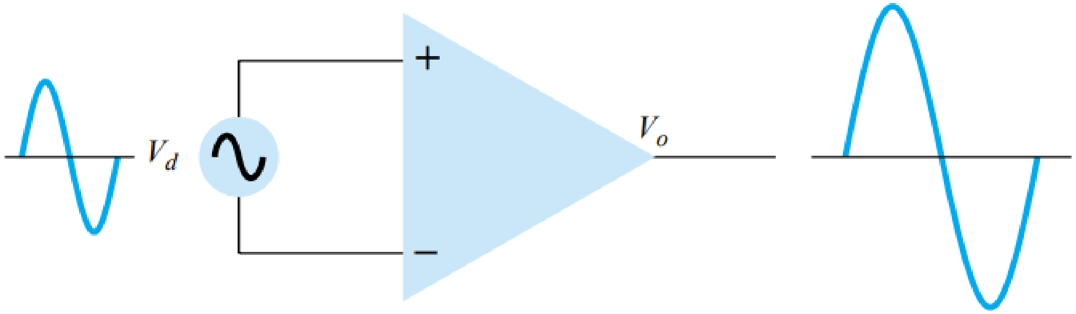
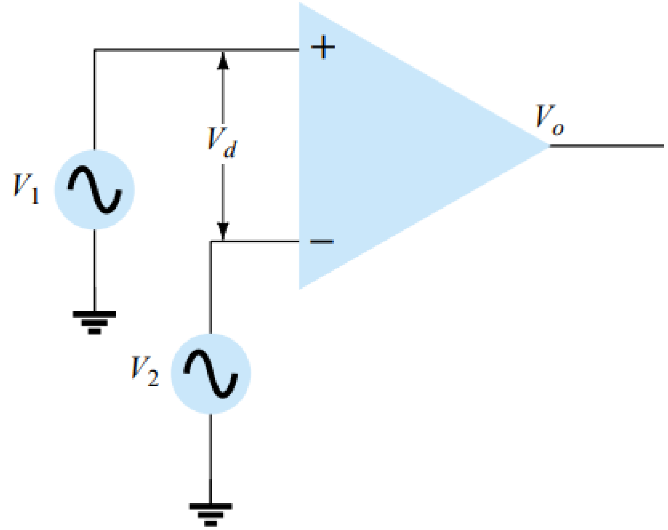


Fig: Input at inverting terminal.

OPAMP: Operational Amplifier

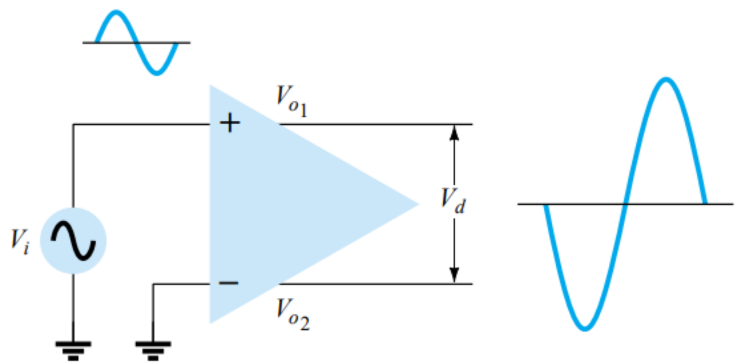
Double-Ended (Differential) Input:

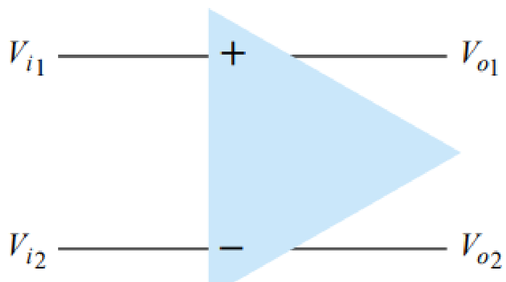




OPAMP: Operational Amplifier

Double-Ended Output:





$$V_o = A_d V_d + A_c V_c$$

$$V_c = \tfrac{1}{2}(V_{i_1} + V_{i_2})$$

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

V_d = difference voltage
V_c = common voltage

A_d = differential gain of the amplifier
A_c = common-mode gain of the amplifier

Common-Mode Rejection Ratio (CMRR):

$$\text{CMRR} = \frac{A_d}{A_c}$$

$$\text{CMRR (log)} = 20 \log_{10} \frac{A_d}{A_c}$$

OPAMP: Operational Amplifier

Determine the output voltage of an op-amp for input voltages of $V_{i_1} = 150\ \mu\text{V}$, $V_{i_2} = 140\ \mu\text{V}$. The amplifier has a differential gain of $A_d = 4000$ and the value of CMRR is:

(a) 100.

(b) 10^5.

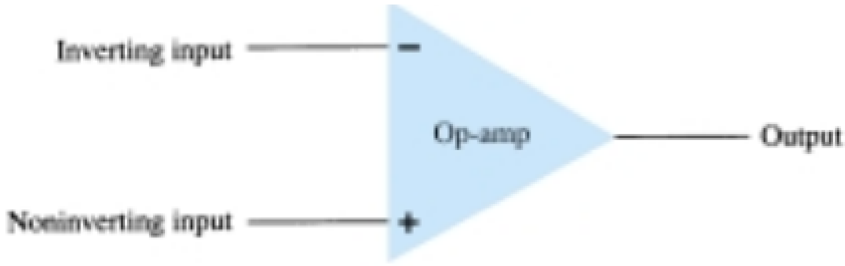
$$V_d = V_{i_1} - V_{i_2} = (150 - 140)\ \mu\text{V} = 10\ \mu\text{V}$$

$$V_c = \frac{1}{2}(V_{i_1} + V_{i_2}) = \frac{150\ \mu\text{V} + 140\ \mu\text{V}}{2} = 145\ \mu\text{V}$$

$$\begin{aligned} V_o &= A_d V_d\left(1 + \frac{1}{\text{CMRR}}\frac{V_c}{V_d}\right) \\ &= (4000)(10\ \mu\text{V})\left(1 + \frac{1}{100}\frac{145\ \mu\text{V}}{10\ \mu\text{V}}\right) \\ &= 40\ \text{mV}(1.145) = \mathbf{45.8\ mV} \end{aligned}$$

$$V_o = (4000)(10\ \mu\text{V})\left(1 + \frac{1}{10^5}\frac{145\ \mu\text{V}}{10\ \mu\text{V}}\right) = 40\ \text{mV}(1.000145) = \mathbf{40.006\ mV}$$

OPAMP: Operational Amplifier



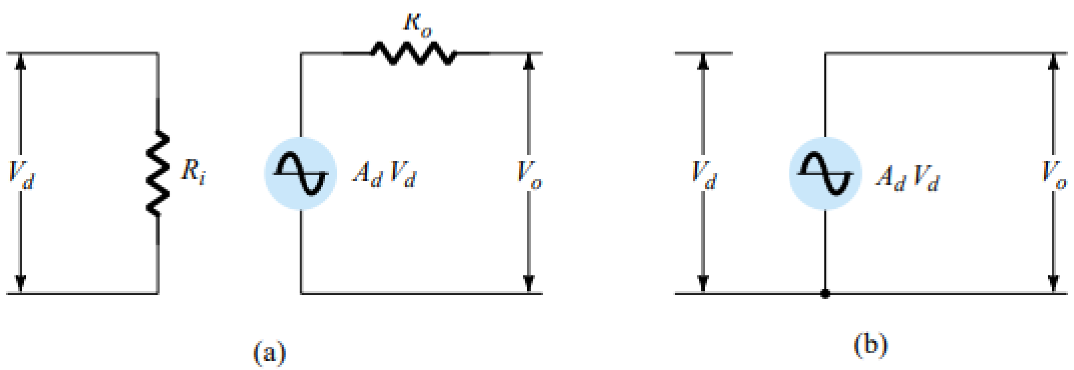
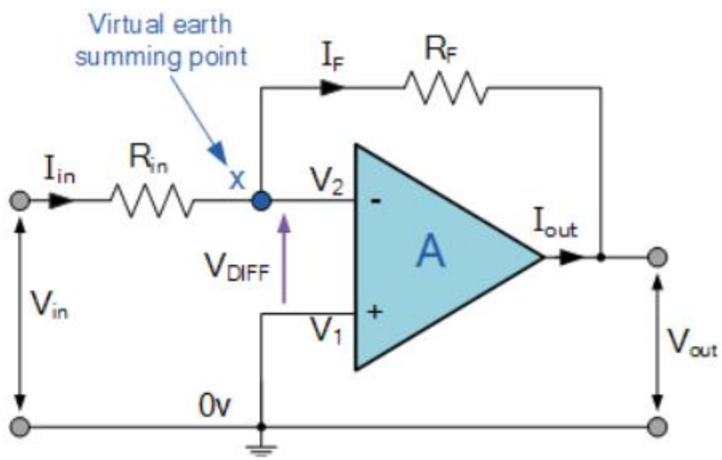


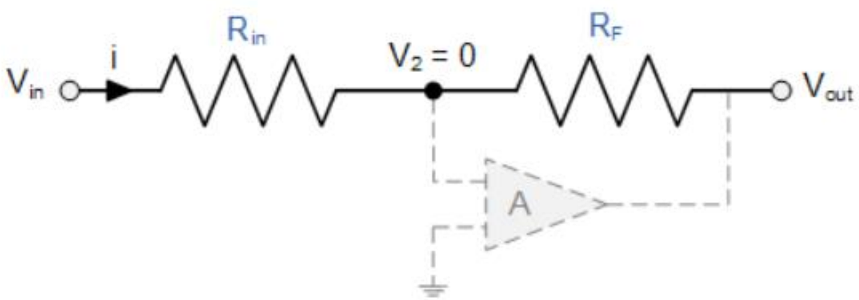
Fig: Ac equivalent of op-amp circuit: (a) practical; (b) ideal.

OPAMP: Operational Amplifier

Inverting Amplifier:



- No Current Flows into the Input Terminals
- The Differential Input Voltage is Zero as V1 = V2 = 0 (Virtual Earth)



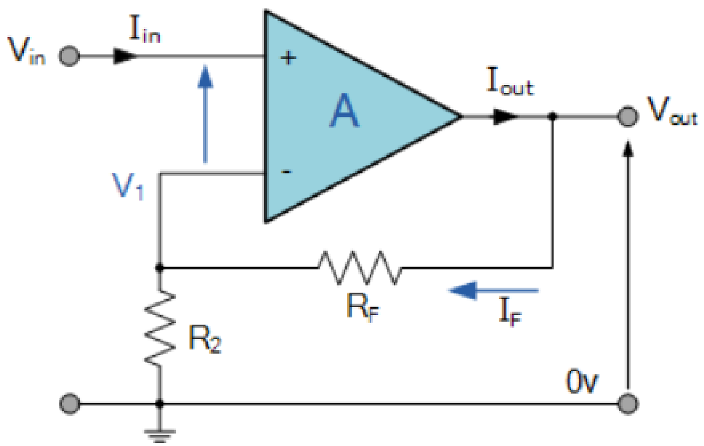
$$i = \frac{Vin - Vout}{Rin + Rf} = \frac{Vin - V2}{Rin} = \frac{V2 - Vout}{Rf} = \frac{Vin}{Rin} - \frac{V2}{Rin} = \frac{V2}{Rf} - \frac{Vout}{Rf}$$

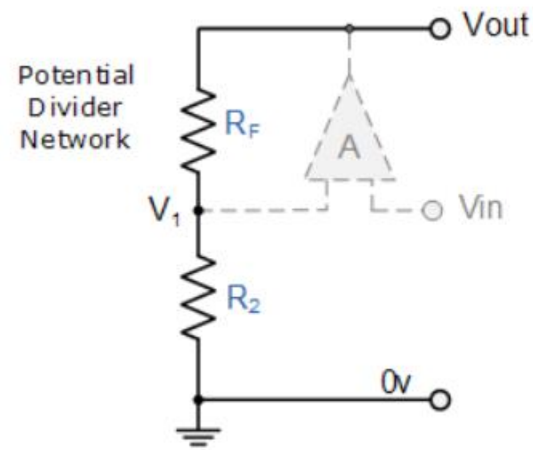
$$\frac{Vin}{Rin} = V2\left[\frac{1}{Rin} + \frac{1}{Rf}\right] - \frac{Vout}{Rf}$$

Closed Loop Gain (Av) is given as, $\frac{Vout}{Vin} = -\frac{Rf}{Rin}$

OPAMP: Operational Amplifier

Noninverting Amplifier:





Ideal $A_d = \frac{V_0}{V_d} = \frac{V_0}{V_1 - V_2} = \infty$

So, $V_1 = V_2$

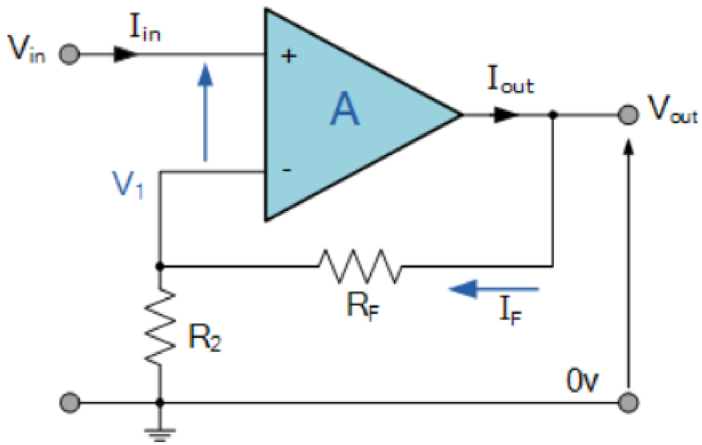
$$V_1 = \frac{R_2}{R_2 + R_F} \times V_{OUT}$$

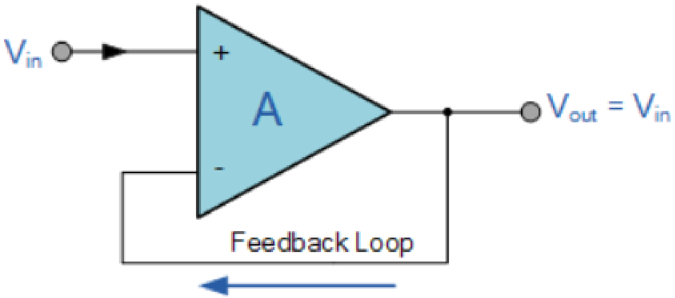
Ideal Summing Point: $V_1 = V_{IN}$

$$A_{(V)} = \frac{V_{OUT}}{V_{IN}} = 1 + \frac{R_F}{R_2}$$

OPAMP: Operational Amplifier

Voltage Follower / Unity Gain Amplifier:



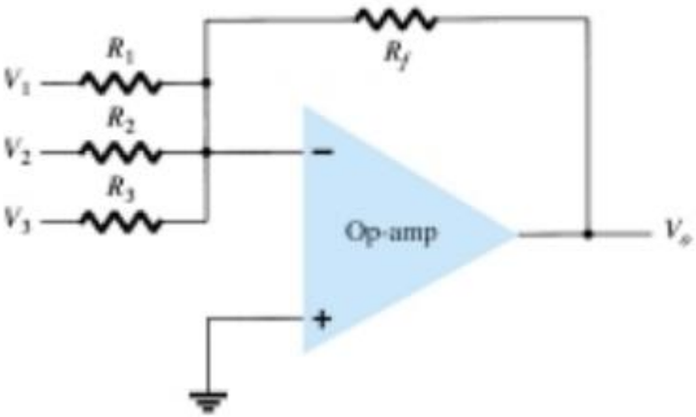


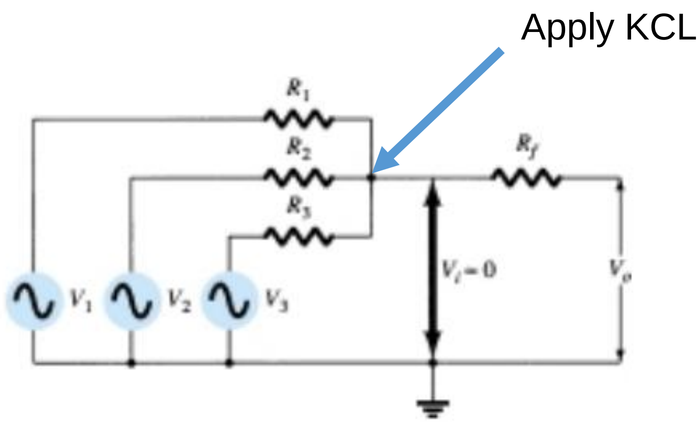
$R_F = 0$

$$A_{(V)} = \frac{V_{OUT}}{V_{IN}} = 1 + \frac{R_F}{R_2} = 1$$

OPAMP: Operational Amplifier

Summing Amplifier:





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

OPAMP: Operational Amplifier

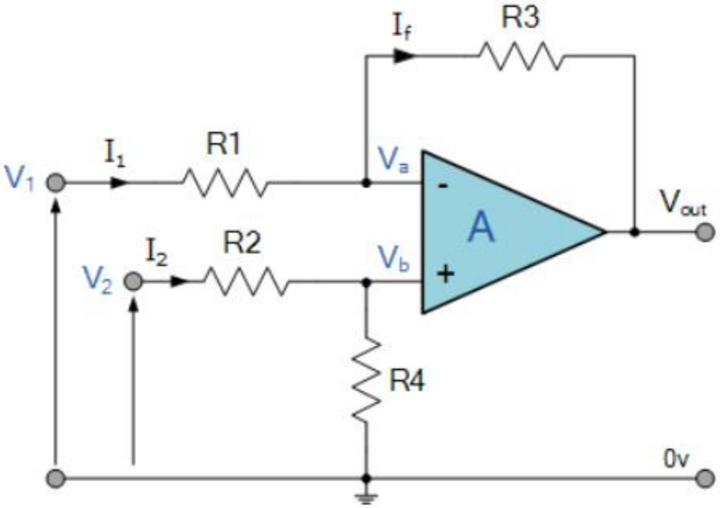
Calculate the output voltage of an op-amp summing amplifier for the following sets of voltages and resistors. Use $R_f = 1\ \text{M}\Omega$ in all cases.
(a) $V_1 = +1$ V, $V_2 = +2$ V, $V_3 = +3$ V, $R_1 = 500\ \text{k}\Omega$, $R_2 = 1\ \text{M}\Omega$, $R_3 = 1\ \text{M}\Omega$.
(b) $V_1 = -2$ V, $V_2 = +3$ V, $V_3 = +1$ V, $R_1 = 200\ \text{k}\Omega$, $R_2 = 500\ \text{k}\Omega$, $R_3 = 1\ \text{M}\Omega$.

(a) $$V_o = -\left[\frac{1000\ \text{k}\Omega}{500\ \text{k}\Omega}(+1\ \text{V}) + \frac{1000\ \text{k}\Omega}{1000\ \text{k}\Omega}(+2\ \text{V}) + \frac{1000\ \text{k}\Omega}{1000\ \text{k}\Omega}(+3\ \text{V})\right]$$
$$= -[2(1\ \text{V}) + 1(2\ \text{V}) + 1(3\ \text{V})] = \mathbf{-7\ V}$$

(b) $$V_o = -\left[\frac{1000\ \text{k}\Omega}{200\ \text{k}\Omega}(-2\ \text{V}) + \frac{1000\ \text{k}\Omega}{500\ \text{k}\Omega}(+3\ \text{V}) + \frac{1000\ \text{k}\Omega}{1000\ \text{k}\Omega}(+1\ \text{V})\right]$$
$$= -[5(-2\ \text{V}) + 2(3\ \text{V}) + 1(1\ \text{V})] = \mathbf{+3\ V}$$

OPAMP: Operational Amplifier

Differential Amplifier / Subtractor:



$$I_1 = \frac{V_1 - V_a}{R_1}, \quad I_2 = \frac{V_2 - V_b}{R_2}, \quad I_f = \frac{V_a - (V_{out})}{R_3}$$

Summing point $V_a = V_b$

and $V_b = V_2\left(\frac{R_4}{R_2 + R_4}\right)$

If $V_2 = 0$, then: $V_{out(a)} = -V_1\left(\frac{R_3}{R_1}\right)$

$$V_{out} = -V_{out(a)} + V_{out(b)}$$

If $V_1 = 0$, then: $V_{out(b)} = V_2\left(\frac{R_4}{R_2 + R_4}\right)\left(\frac{R_1 + R_3}{R_1}\right)$

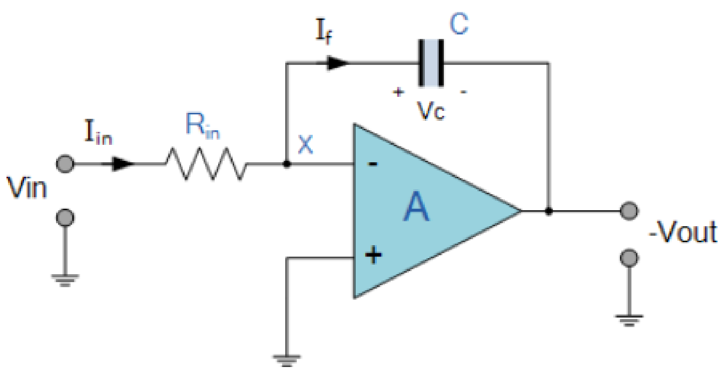
When resistors, R1 = R2 and R3 = R4

$$V_{out} = -V_1\left(\frac{R_3}{R_1}\right) + V_2\left(\frac{R_4}{R_2 + R_4}\right)\left(\frac{R_1 + R_3}{R_1}\right)$$

$$V_{OUT} = \frac{R_3}{R_1}\left(V_2 - V_1\right)$$

OPAMP: Operational Amplifier

Integrator Amplifier:



$$V_c = \frac{Q}{C}, \qquad V_c = V_x - V_{out} = 0 - V_{out}$$

$$-\frac{dV_{out}}{dt} = \frac{dQ}{Cdt} = \frac{1}{C}\frac{dQ}{dt}$$

$$I_{in} = \frac{V_{in} - 0}{R_{in}} = \frac{V_{in}}{R_{in}}$$

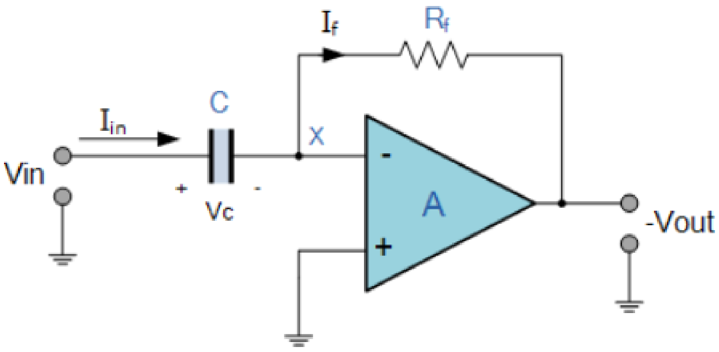
$$I_f = C\frac{dV_{out}}{dt} = C\frac{dQ}{Cdt} = \frac{dQ}{dt} = \frac{dV_{out}.C}{dt}$$

$$I_{in} = I_f = \frac{V_{in}}{R_{in}} = \frac{dV_{out}.C}{dt}$$

$$\boxed{V_{out} = -\frac{1}{R_{in}C}\int_0^t V_{in}\,dt = -\int_0^t V_{in}\frac{dt}{R_{in}.C}}$$

OPAMP: Operational Amplifier

Differentiator Amplifier:



$$I_{IN} = I_F \text{ and } I_F = -\frac{V_{OUT}}{R_F}$$

$$Q = C \times V_{IN}$$

$$\frac{dQ}{dt} = C\frac{dV_{IN}}{dt}$$

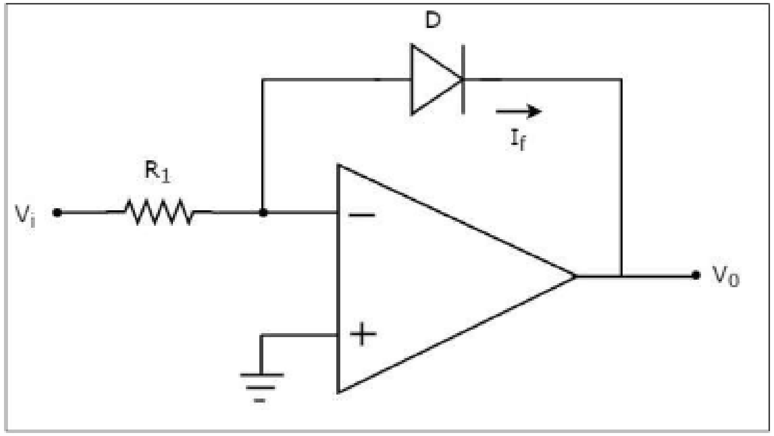
$$I_{IN} = C\frac{dV_{IN}}{dt} = I_F$$

$$-\frac{V_{OUT}}{R_F} = C\frac{dV_{IN}}{dt}$$

$$V_{OUT} = -R_F C\frac{dV_{IN}}{dt}$$

OPAMP: Operational Amplifier

Logarithmic Amplifier:



$$0 - V_i/R_1 + I_f = 0$$

$$I_f = V_i/R_1$$

When the diode is forward biased

$$I_f = I_s e^{(V_f/nV_T)}$$

$$0 - V_f - V_0 = 0$$

$$V_f = -V_0$$

$$I_f = I_s e^{(-V_0/nV_T)}$$

$$V_i/R_1 = I_s e^{(-V_0/nV_T)}$$

$$V_i/R_i I_s = e^{(-V_0/nV_T)}$$

$$\ln(V_i/R_1 I_s) = -V_0/nV_T$$

$$V_0 = -nV_T \ln(V_i/R_1 I_s)$$

Where,

I_s is the saturation current of the diode,

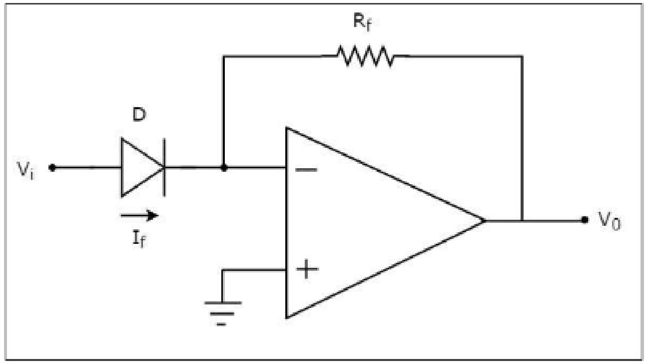
V_f is the voltage drop across diode, when it is in forward bias,

V_T is the diode's thermal equivalent voltage.

Source: https://ae-iitr.vlabs.ac.in/exp/log-antilog-amplifier/theory.html#:~:text=A%20logarithmic%20amplifier%20is%20an,connected%20to%20its%20inverting%20terminal.

OPAMP: Operational Amplifier

Anti-Logarithmic Amplifier



$$-I_f + 0 - V_0/R_f = 0$$

$$V_0 = -I_f * R_f$$

$$I_f = I_s e^{(V_f/nV_T)}$$

$$V_0 = -R_f I_s e^{(V_f/nV_T)}$$

$$V_i - V_f = 0$$

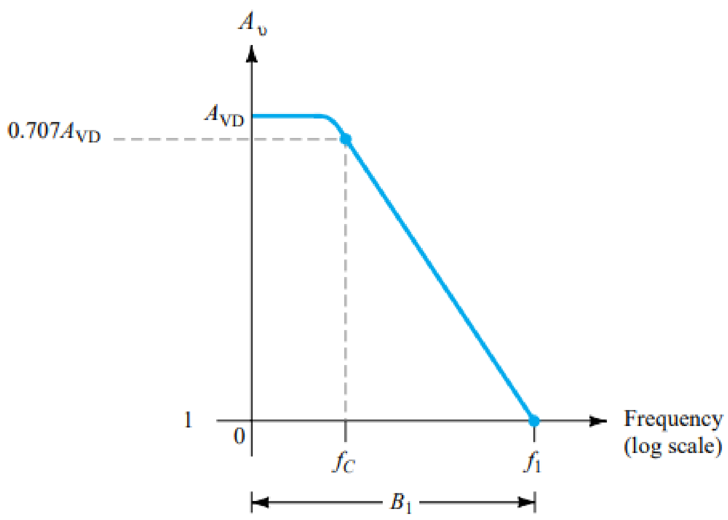
$$V_i = V_f$$

$$V_0 = -R_f I_s e^{(V_i/nV_T)}$$

Source: https://ae-iitr.vlabs.ac.in/exp/log-antilog-amplifier/theory.html#:~:text=A%20logarithmic%20amplifier%20is%20an,connected%20to%20its%20inverting%20terminal.

OPAMP: Operational Amplifier

OP-AMP PARAMETERS:



Cutoff frequency (f_c): The frequency at which differential gain of the OPAMP becomes 0.707 times the maximum differential voltage gain.

Unity-gain bandwidth (B1): The frequency band where differential voltage gain value becomes 1.

$$f_1 = A_{VD} f_C$$

Slew rate (SR): Maximum rate at which amplifier output can change

$$\mathrm{SR} = \frac{\Delta V_o}{\Delta t}$$

OPAMP: Operational Amplifier

For an op-amp having a slew rate of SR = 2 V/μs, what is the maximum closed-loop voltage gain that can be used when the input signal varies by 0.5 V in 10 μs?

Solution

Since $V_o = A_{CL}V_i$, we can use

$$\frac{\Delta V_o}{\Delta t} = A_{CL}\frac{\Delta V_i}{\Delta t}$$

from which we get

$$A_{CL} = \frac{\Delta V_o/\Delta t}{\Delta V_i/\Delta t} = \frac{\text{SR}}{\Delta V_i/\Delta t} = \frac{2\ \text{V}/\mu\text{s}}{0.5\ \text{V}/10\ \mu\text{s}} = \mathbf{40}$$

Any closed-loop voltage gain of magnitude greater than 40 would drive the output at a rate greater than the slew rate allows, so the maximum closed-loop gain is 40.

OPAMP: Operational Amplifier

Maximum Signal Frequency

The maximum frequency that an op-amp may operate at 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

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

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

$$2\pi f K \leq \text{SR}$$

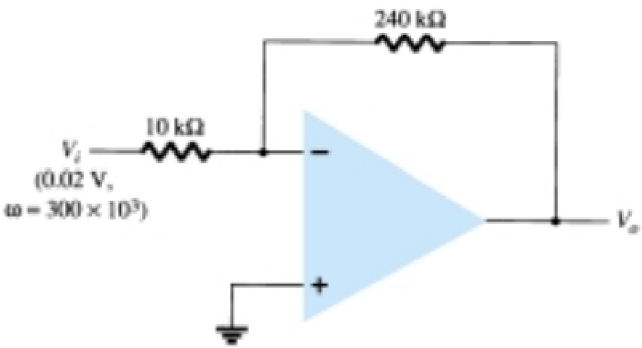
$$\omega K \leq \text{SR}$$

$$\boxed{\begin{aligned} f &\leq \frac{\text{SR}}{2\pi K} \qquad \text{Hz} \\ \omega &\leq \frac{\text{SR}}{K} \qquad \text{rad/s} \end{aligned}}$$

Additionally, the maximum frequency, f, is also limited by the unity-gain bandwidth.

OPAMP: Operational Amplifier

For the signal and circuit of Fig. 14.29, determine the maximum frequency that may be used. Op-amp slew rate is SR 0.5 V/µs.



Solution

For a gain of magnitude

$$A_{CL} = \left|\frac{R_f}{R_1}\right| = \frac{240\ \text{k}\Omega}{10\ \text{k}\Omega} = 24$$

the output voltage provides

$$K = A_{CL}V_i = 24(0.02\ \text{V}) = 0.48\ \text{V}$$

$$\omega \leq \frac{\text{SR}}{K} = \frac{0.5\ \text{V}/\mu\text{s}}{0.48\ \text{V}} = \mathbf{1.1 \times 10^6\ rad/s}$$

Since the signal's frequency, $\omega = 300 \times 10^3$ rad/s, is less than the maximum value determined above, no output distortion will result.