Analog & Digital Electronics

Course No: PH-218

Lec-23: Operational Amplifiers

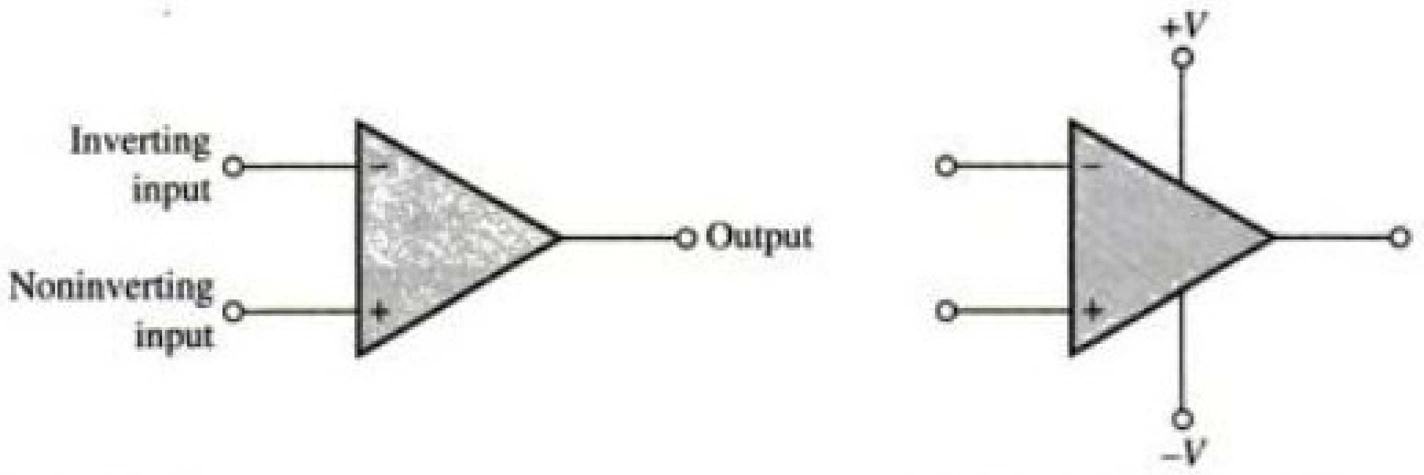
Course Instructor:

❖ **Dr. A. P. VAJPEYI**

Department of Physics,
Indian Institute of Technology Guwahati, India

Operational amplifier (OP-AMP)

An Op-Amp is a very high gain differential amplifier with very high input impedance (typically a few Mega ohm) and a low output impedance (less than 100Ω)



- **If the signal applied to the input terminal, results in opposite polarity output then input terminal is called inverting input, and if output is of same polarity input terminal is called non-inverting input.**

Operational amplifier (OP-AMP)

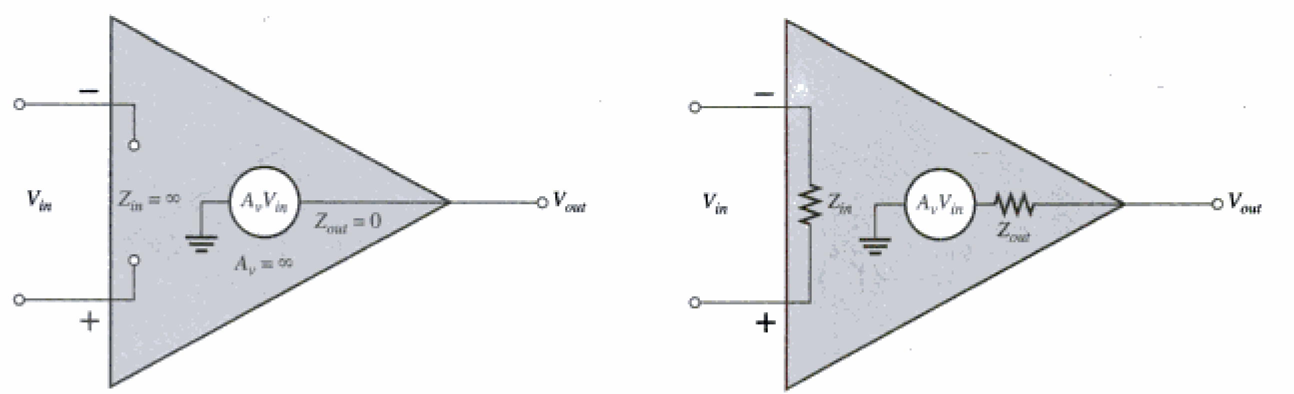
- **Earlier, op-amp were used primarily to perform mathematical operation such as summation, subtraction, differentiation and integration etc. so named as op-amp.**

- **Typical application of op-amp includes – voltage amplitude change, oscillators, filter circuits and in instrumentation circuits.**

Characteristics of an Ideal Operational amplifier

Ideal op-amp has following characteristics -

- **Input Resistance Ri= ∞**
- **Output Resistance Ro= 0**
- **Voltage Gain A = ∞**
- **Bandwidth = ∞**
- **Perfect balance i.e vo= 0 when v1= v2**
- **Characteristics do not drift with temperature**



(a) Ideal op-amp representation (b) Practical op-amp representation

Concept of Virtual Ground

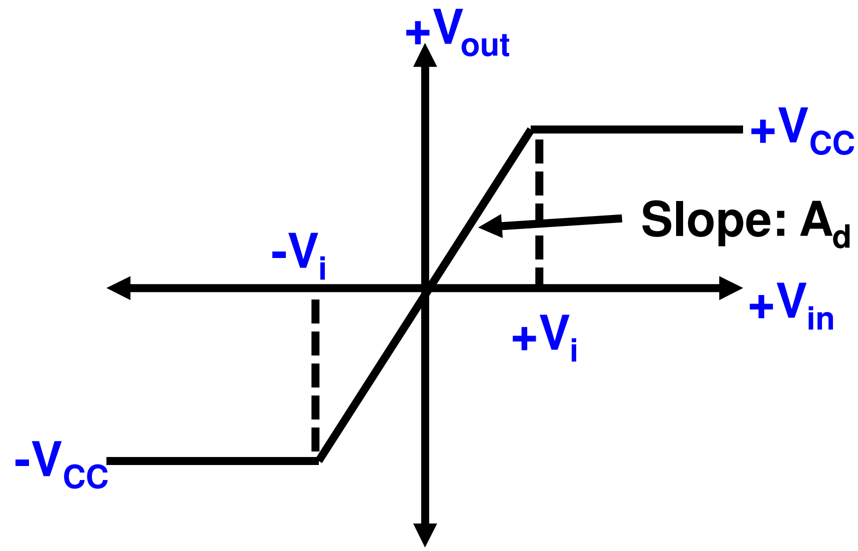
➢ An Op-Amp has a very high gain typically order of 10^5.

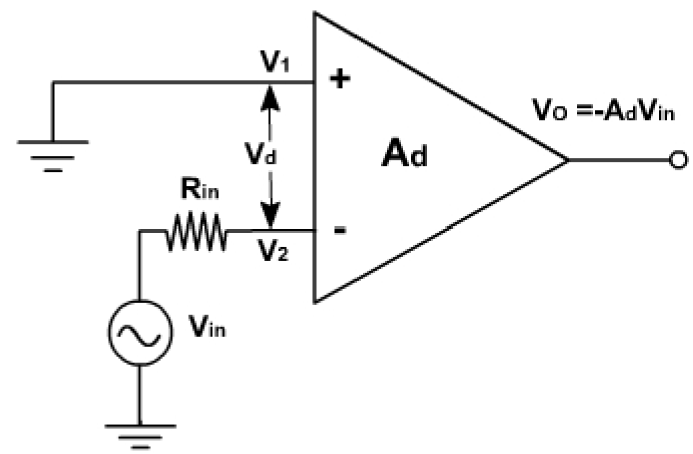
➢ If power supply voltage V_{cc} =15V Then maximum input voltage which can be applied

$$V_d = V_{cc} / A_d = 15 / 10^5 = 150\mu V$$

i.e. Op-Amp can work as a linear amplifier (from $+V_i$ to $-V_i$) if input voltage is less than 150µV. Above that Op-Amp saturates.

➢ if V_1 is grounded then V_2 can not be more than 150 µV which is very very small and close to ground.





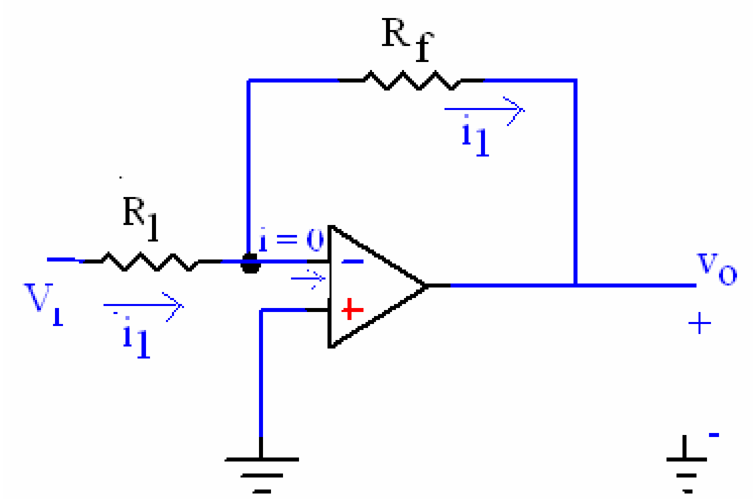
➢ Therefore V_2 can also be considered at ground if V_1 is at ground. Physically V_2 is not connected to the ground yet we considered V_2 at ground that is called virtual ground.

Need of negative feedback in op-amp

- Any input signal slightly greater than zero drive the output to saturation level because of very high gain.

- Thus when operated in open-loop, the output of the OPAMP is either negative or positive saturation or switches between positive and negative saturation levels (comparator). Therefore open loop op-amp is not used in linear applications.

- With negative feedback, the voltage gain (A_{cl}) can be reduced and controlled so that op-amp can function as a linear amplifier.

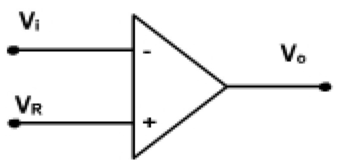


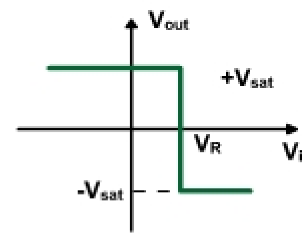
- In addition to provide a control and stable voltage gain, negative feedback provides control of input & output impedance and amplifier bandwidth.

Op-Amp as a Comparator

➢ **A comparator is a type of op-amp that compares two input voltage and produces an output in either of two states indicating the greater than or less than relationship of the input.**

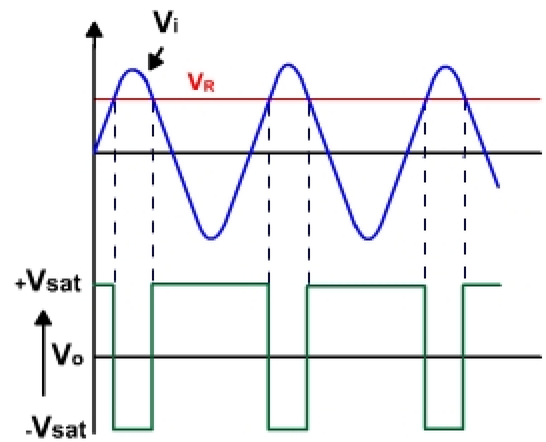
➢ **When the inverting voltage is larger than the noninverting voltage the comparator produces a low output voltage ($-V_{sat}$). When the inverting output is less than the non-inverting input the output is high ($+V_{sat}$).**





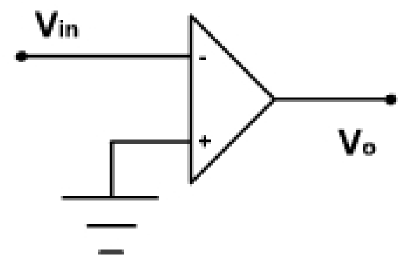
$$v_O = -V_{sat} \text{ if } v_i > V_R$$
$$= +V_{sat} \text{ if } v_i < V_R$$

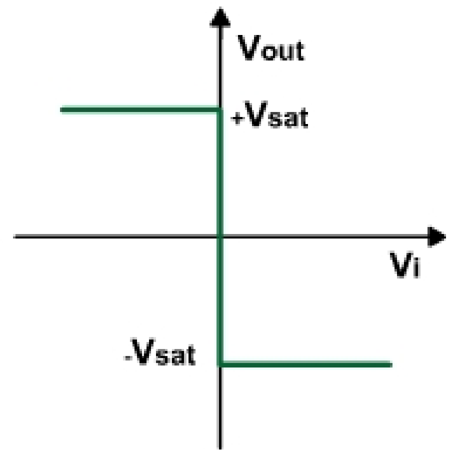
➢**If open loop gain of op-amp is 10^5 then differential input voltage of only 0.25 mV will produce output voltage of = 25V. However, most of op-amp have limitation of maximum power supply voltage of 15V hence device would be driven to saturation.**



Op-Amp as a Comparator

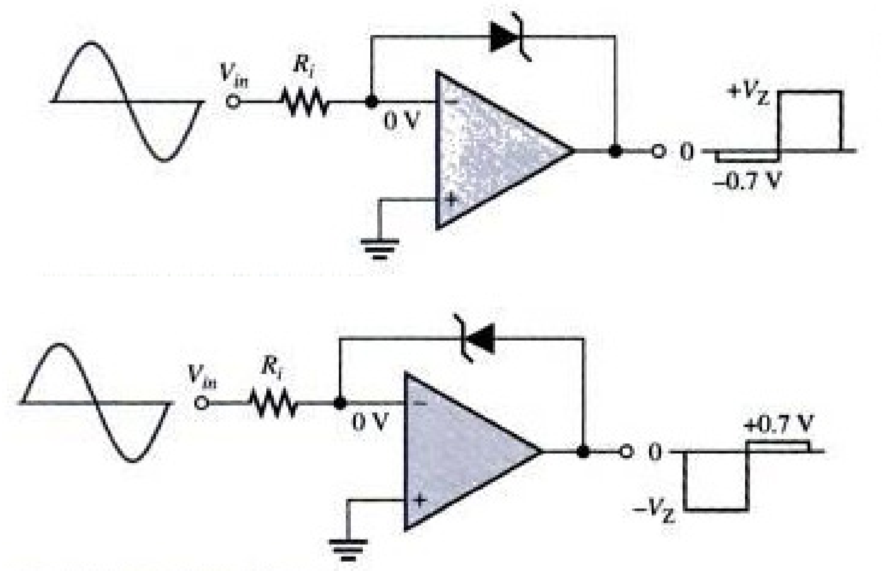
If $V_R = 0$, then slightest input voltage (in mV) is enough to saturate the OPAMP and the circuit acts as **zero crossing detector.** The more the open loop gain of OPAMP, the smaller the voltage required to saturate the output. If v_d required is very small then the characteristic is a vertical line.





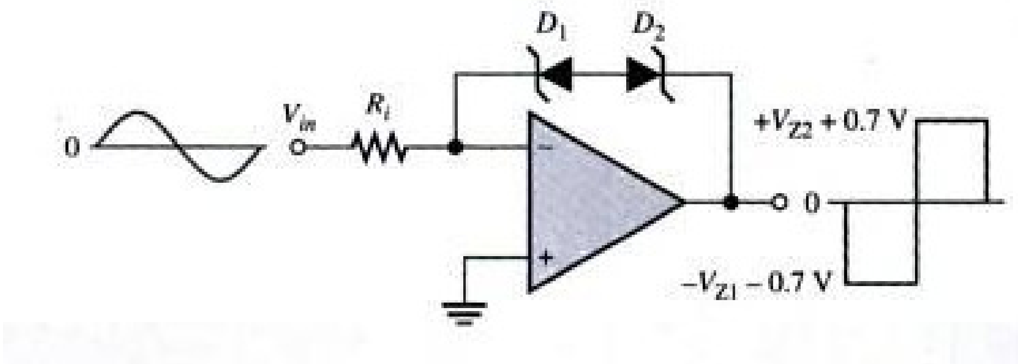
Output Bounding

The output voltage of a comparator can be limited to a value less than the saturation voltage by connecting a zener diode with the comparator. This process of limiting the output voltage is called bounding.



Comparator: Output Bounding

Two zener diode connected back to back with a comparator limit the output voltage to the zener voltage plus the voltage drop (0.7V) of the forward bias zener diode, both positively and negatively.



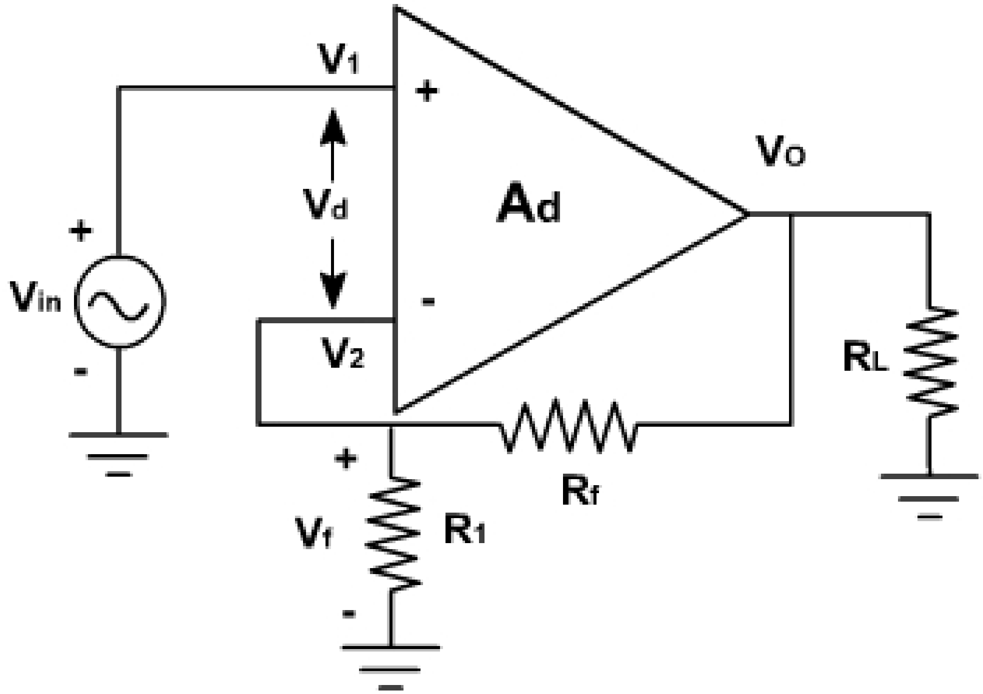
Noninverting Amplifier

- The differential input to the op-amp (V_{in}-V_f) will be amplified by the open loop gain and produces an output voltage.

$$V_o = A_d(V_{in} - V_f)$$

$$V_f = \beta V_o = \frac{R_1}{R_1 + R_f} V_o$$

$$\frac{V_o}{V_{in}} = \frac{A_d}{1 + \beta A_d} = \frac{1}{\beta}$$



- Since $\beta A_d >> 1$

$$\frac{V_o}{V_{in}} = \frac{1}{\beta} = \frac{R_1 + R_f}{R_1}$$

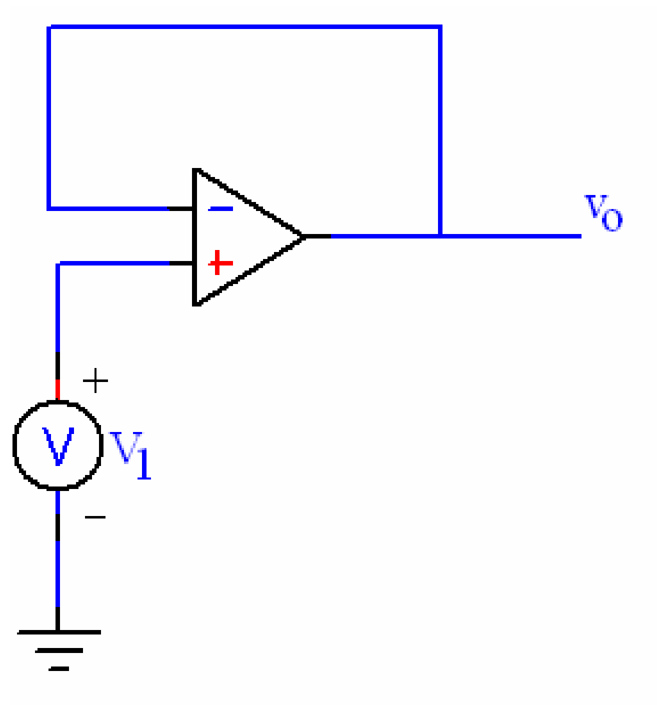
$$V_o = (1 + \frac{R_f}{R_1})V_{in}$$

Voltage Follower

➢ **The lowest gain that can be obtained from a non-inverting amplifier with feedback is 1.**

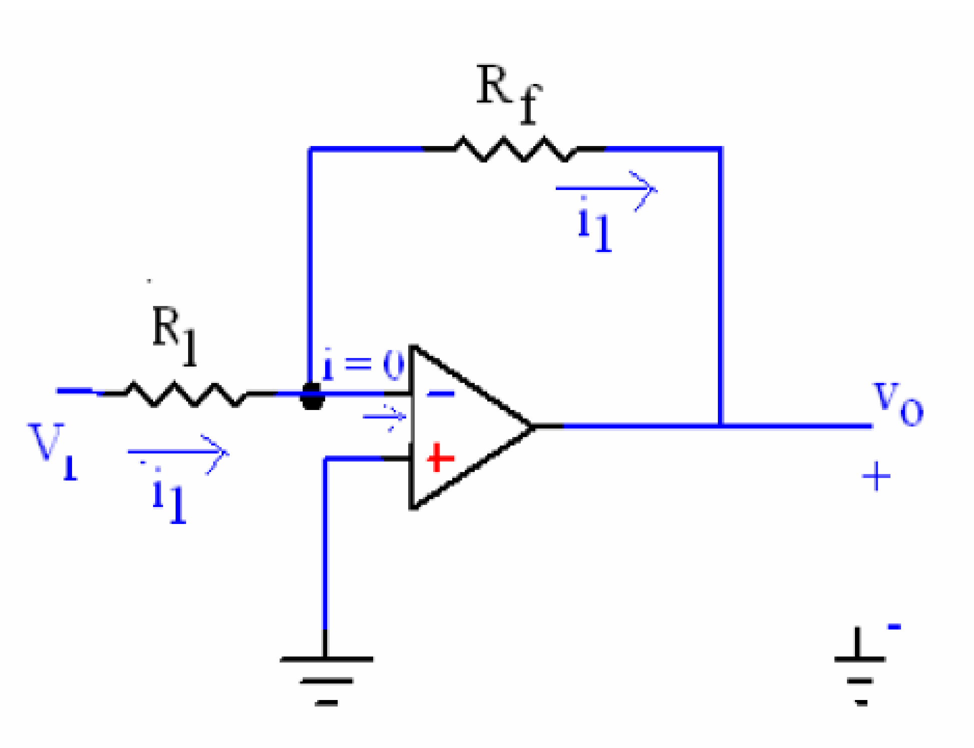
➢ **When the non-inverting amplifier gives unity gain, it is called voltage follower because the output voltage is equal to the input voltage and in phase with the input voltage. In other words the output voltage follows the input voltage.**

$$V_o = V_{in}$$



➢ **Voltage follower has very high input impedance and very low output impedance hence used as a buffer amplifier for interfacing high impedance source and low impedance load.**

Inverting Amplifier or Scale Changer



Using KVL,

$v_1 - i_1R_1 = 0$

$\Rightarrow \ i_1 = v_1/R_1$

&

$0 - i_1R_f - v_o = 0$

or, $v_o = -i_1R_f = -v_1R_f/R_1$

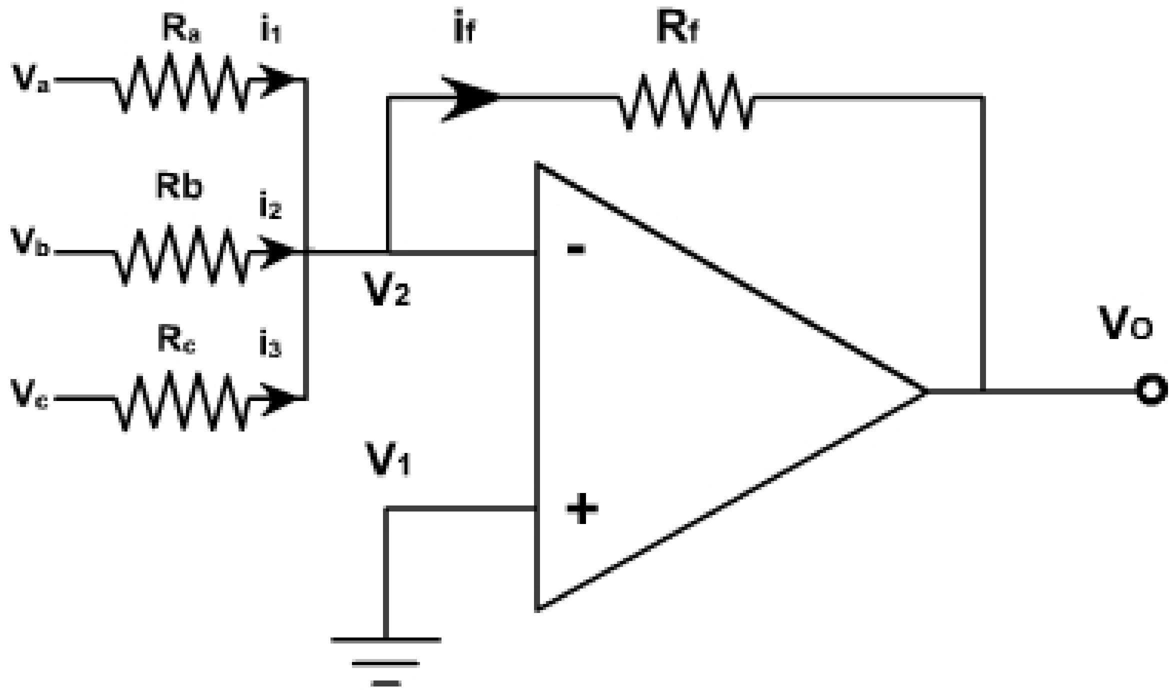
$v_0/v_1 = -R_f/R_1$

If $R_1 = R_f$ then $v_O = -v_1$, the circuit behaves like an inverter.

If $R_f / R_1 = K$ (a constant) then the circuit is called inverting amplifier or scale changer voltages.

Summing Amplifier

For an ideal OPAMP, $v_1 = v_2$. The current drawn by OPAMP is zero. Thus, applying KCL at v_2 node



$$i_1 + i_2 + i_3 = i_f$$

$$\frac{V_a}{R_a} + \frac{V_b}{R_b} + \frac{V_c}{R_c} = \frac{V_o}{R_f}$$

$$V_o = -\left(\frac{R_f}{R_a}V_a + \frac{R_f}{R_b}V_b + \frac{R_f}{R_c}V_c\right)$$ If $R_a = R_b = R_c = R$; then $$V_o = -\frac{R_f}{R}(V_a + V_b + V_c)$$

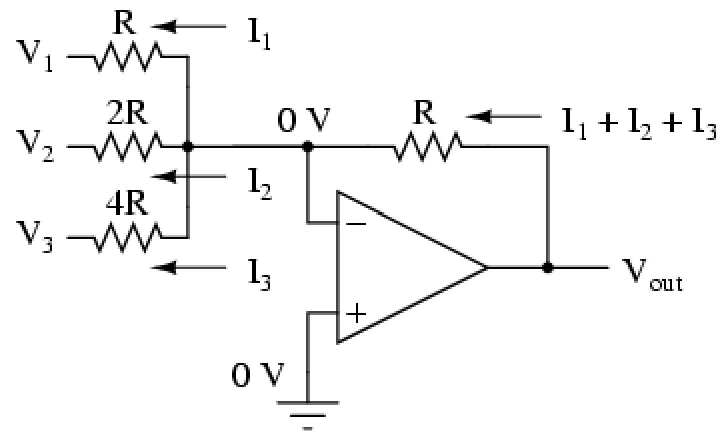
If R_f = R then $v_O = -(v_a + v_{bf} + v_c)$, the circuit behaves like a inverting summer.

If R / R_f = n where n is number of inputs then the circuit behave like a averaging amplifier.

Summing Amplifier as D/A converter

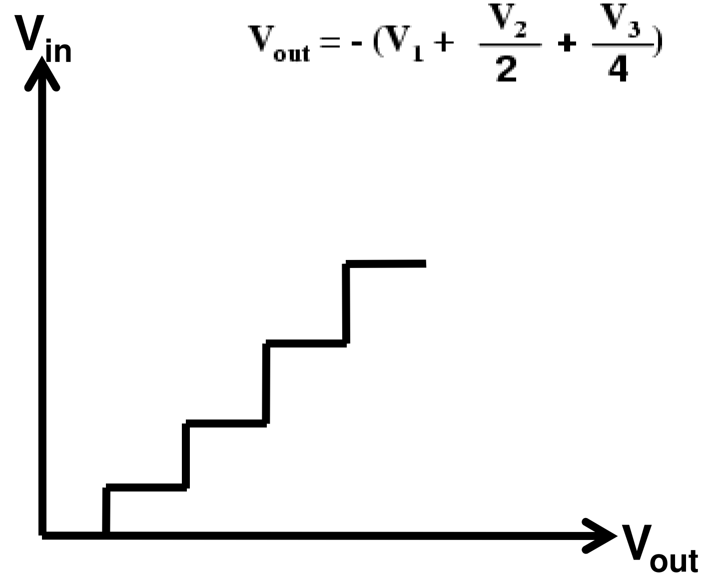
A digital to analog (D/A) converter is a weighted summing circuit that produces an output equal to the weighted sum of inputs.

The weight is same as the gain of the channel.



$$V_o = -(\frac{R_f}{R_a}V_a + \frac{R_f}{R_b}V_b + \frac{R_f}{R_c}V_c)$$

Binary Input	Output
000	0
001	-0.125
010	-0.50
011	-0.625
100	-1.00
101	-1.125
110	-1.50
111	-1.625



$$V_{out} = -(V_1 + \frac{V_2}{2} + \frac{V_3}{4})$$