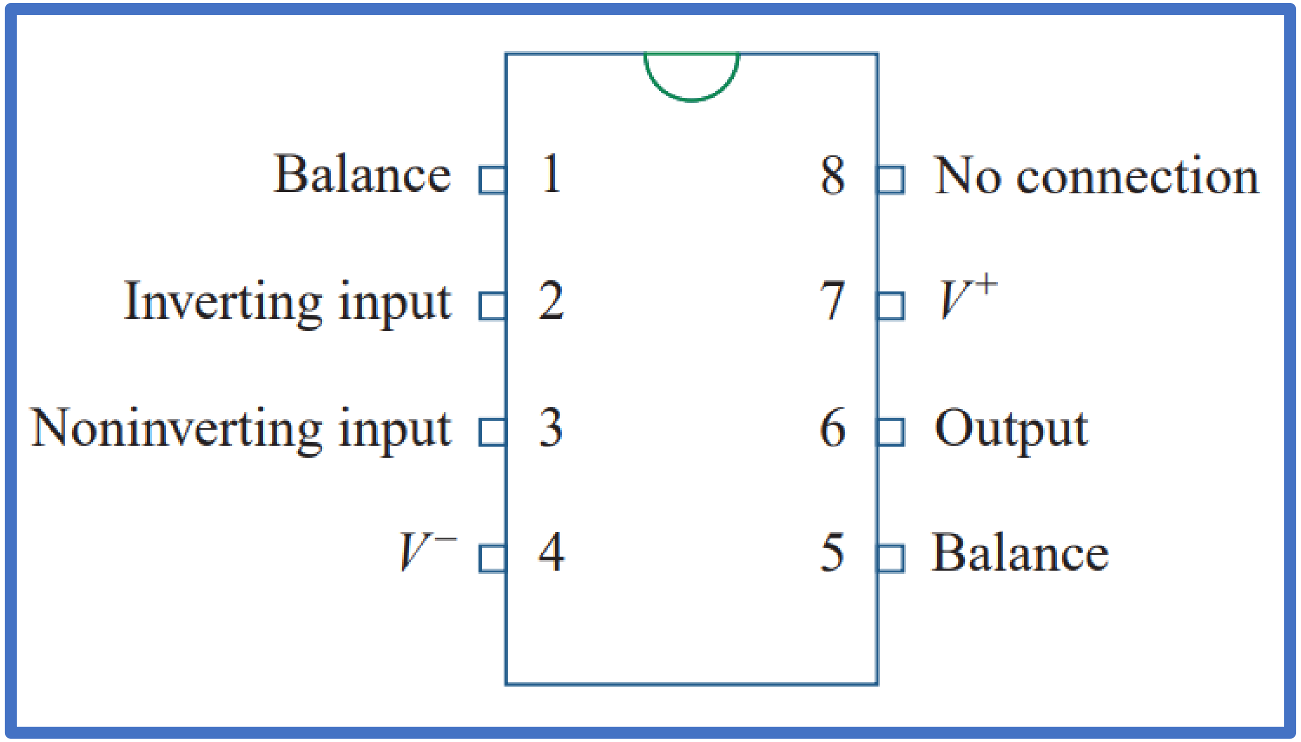
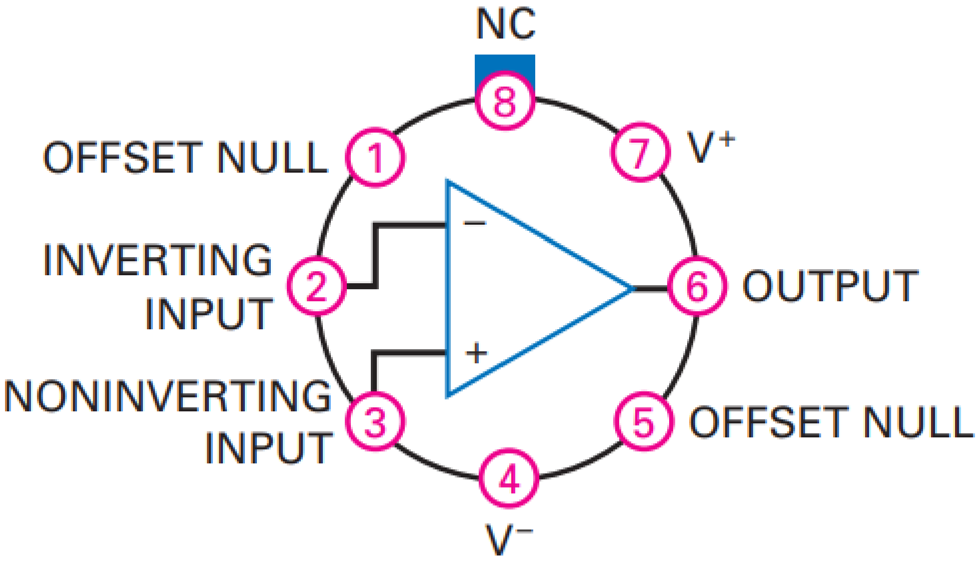
Operational Amplifier (Op-amp)

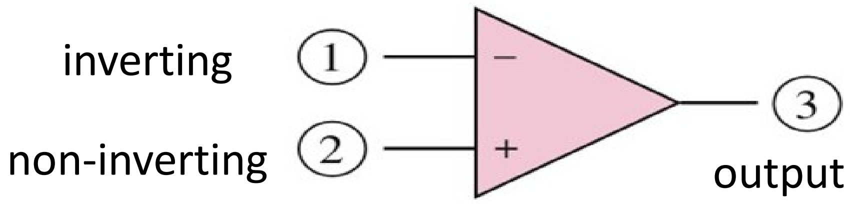


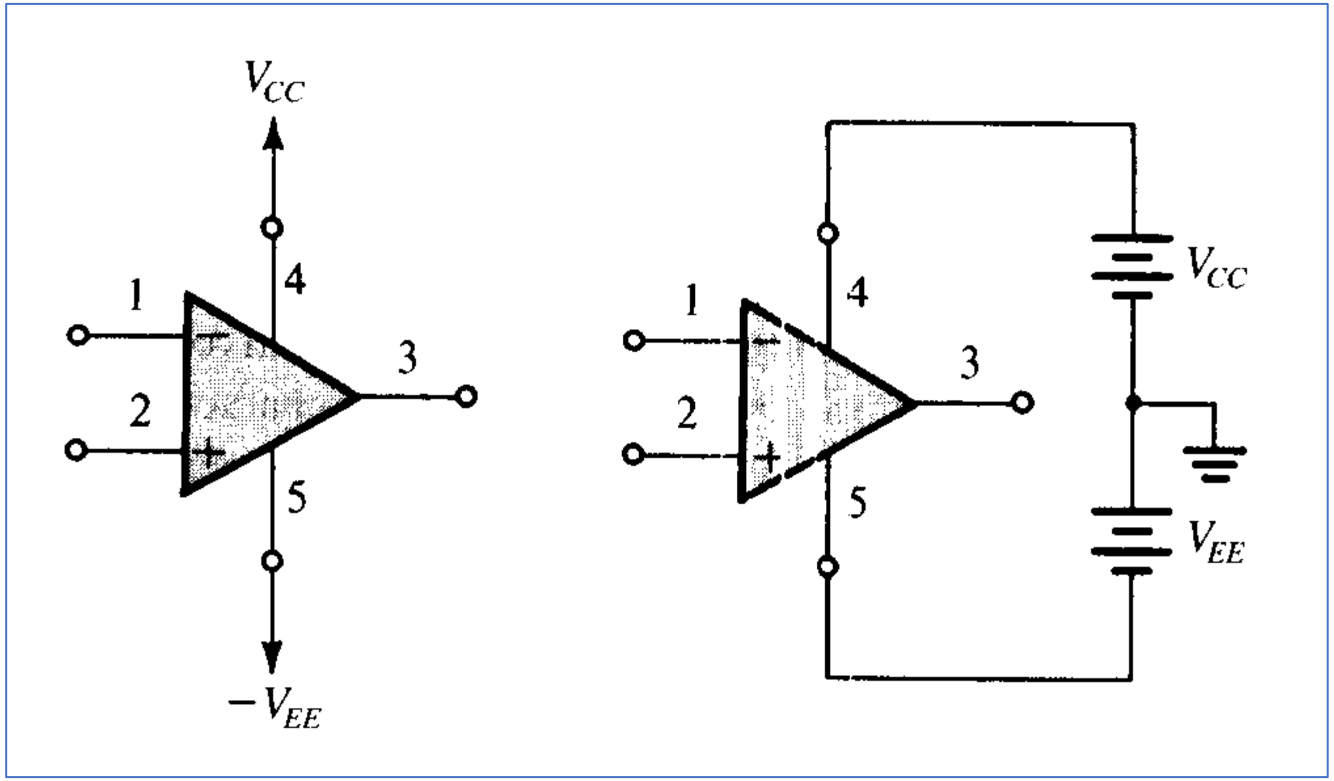
Metal Can Package



Ideal Op-amp

- Op-amp has three terminals: two input terminals and one output terminal
- Terminals 1 and 2 are input terminals, and 3 is the output terminal

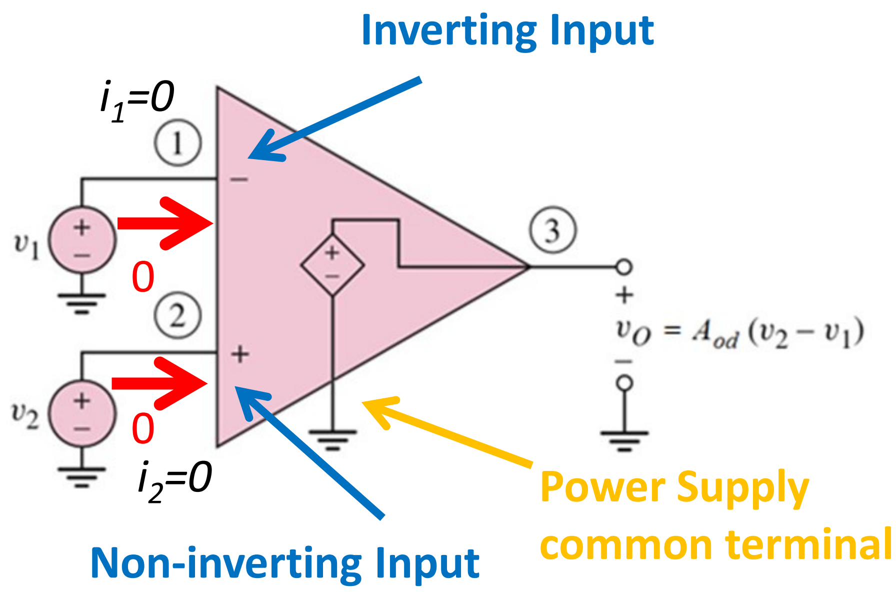




*Terminals represented here are not pin numbers

Characteristics of an Ideal Op-amp

- Input impedance of an ideal Op-amp is infinite and output impedance of an ideal Op-amp in zero



- The output is in phase with v_2 and out of phase with v_1
- Terminal 1 is inverting input terminal and terminal 2 is non-inverting terminal

Characteristics of an Ideal Op-amp

- The output voltage at terminal-3 is $A(v_2 - v_1)$
- Op-amp responds to difference signal and rejects common signal at the input
- This property is called common mode rejection
- An ideal op-amp has zero common mode gain or equivalently infinite common mode rejection
- Op-amp is differential input single ended output amplifier
- Ideal op-amp has infinite bandwidth
- Ideal op-amp has infinite open loop gain A

Characteristics of an ideal Op-amp

Parameter	Value/Description (Ideal)
Input Impedance	Infinite
Output Impedance	Zero
Common-mode gain	Zero
Common-mode rejection ratio	Infinite
Open-loop gain	Infinite
Bandwidth	Infinite

When the same input signals are applied to both inputs, common-mode operation results, as shown in Fig. Ideally, the two inputs are equally amplified, and since they result in opposite-polarity signals at the output, these signals cancel, resulting in 0-V output. Practically, a small output signal will result.

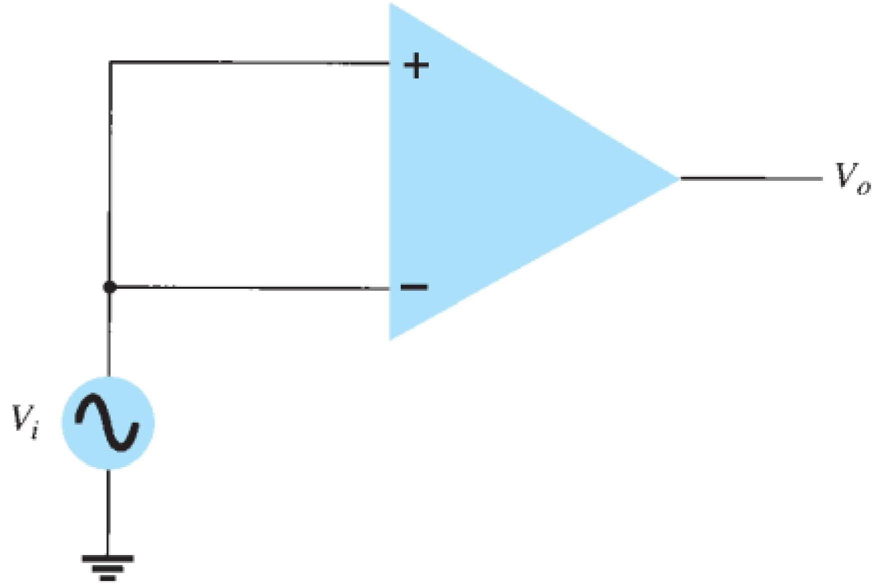


Fig. Common-mode operation

Differential and Common Mode Signals

- Differential input signal is difference between two input signals v_1 (inverting) and v_2 (non-inverting) i.e.,

$$v_{1d} = (v_2 - v_1)$$

- Common mode input signal is an average of two input signals i.e.,

$$v_{1cm} = \frac{v_1 + v_2}{2}$$

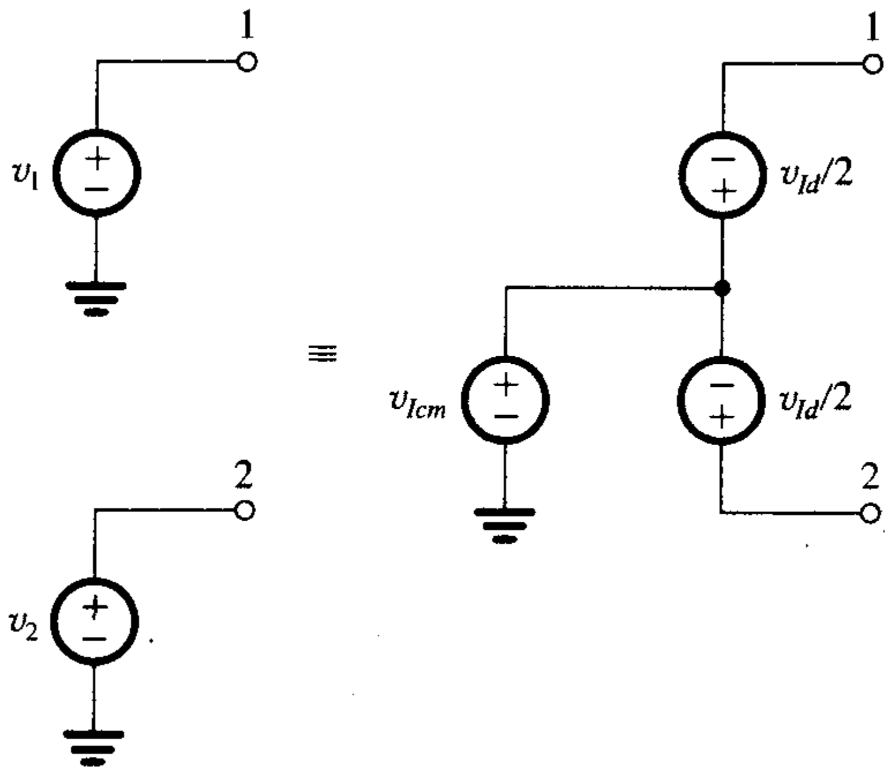
- Expressing inputs and output in terms of v_1 and v_2 i.e.,

$$v_1 = v_{1cm} - \frac{v_{ld}}{2}$$

$$v_2 = v_{1cm} + \frac{v_{ld}}{2}$$

$$A = \frac{v_o}{v_{in}} = \frac{v_o}{v_{1d}}$$

Differential and Common Mode Signals



Example:

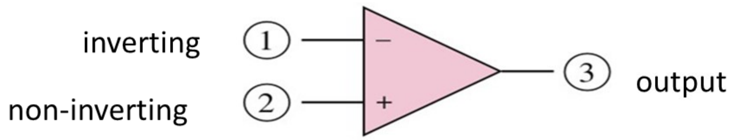
Consider an ideal op-amp, except that its open-loop gain A = 10^3. The op-amp is used in a feedback circuit, and the voltages at two of its three signal terminals are measured. Here v_1 is the inverting input, v_2 is the non-inverting input, and v_3 is the output node. In each of the following cases, use the measured values to find the expected value of the voltage at the third terminal. Also, give the differential and common-mode input signals in each case. (a) $v_2 = 0$ V and $v_3 = 2$ V; (b) $v_1 = 1.002$ V and $v_2 = 0.998$ V; (c) $v_1 = -3.6$ V and $v_3 = -3.6$ V

Question	v_1	v_2	$v_o = v_3$	v_{1d}	v_{1cm}
a	**-2 mV**	0 V	2 V	**2 mV**	**-1 mV**
b	1.002 V	0.998 V	**-4 V**	**-4 mV**	**1 V**
c	-3.6 V	**-3.6036 V**	-3.6 V	**-3.6 mV**	**-3.6018 V**

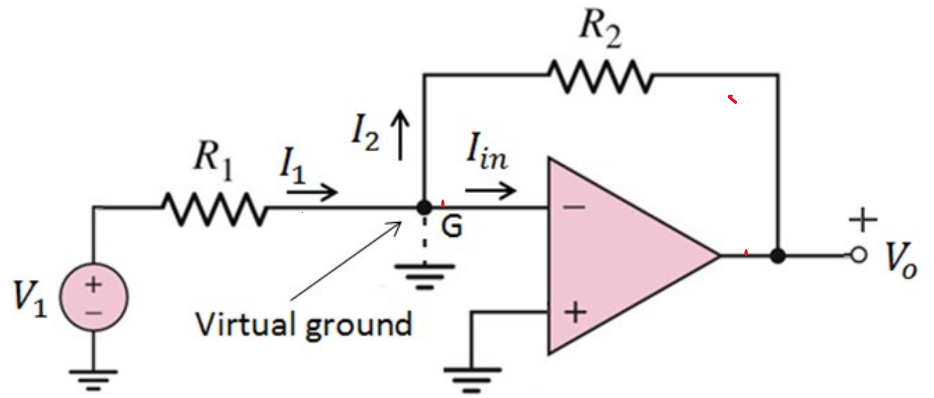
Formulae used: $v_{1d} = (v_2 - v_1)$ $\quad A = \dfrac{v_o}{v_{in}} = \dfrac{v_o}{v_{1d}}$ $\quad v_{1cm} = \dfrac{v_1 + v_2}{2}$

$$v_2 = v_{1cm} + \frac{v_{1d}}{2} \qquad v_1 = v_{1cm} - \frac{v_{1d}}{2}$$

Inverting Op-amp



- Op-amp is connected to passive components i.e., R_1 and R_2



- The close loop gain G,

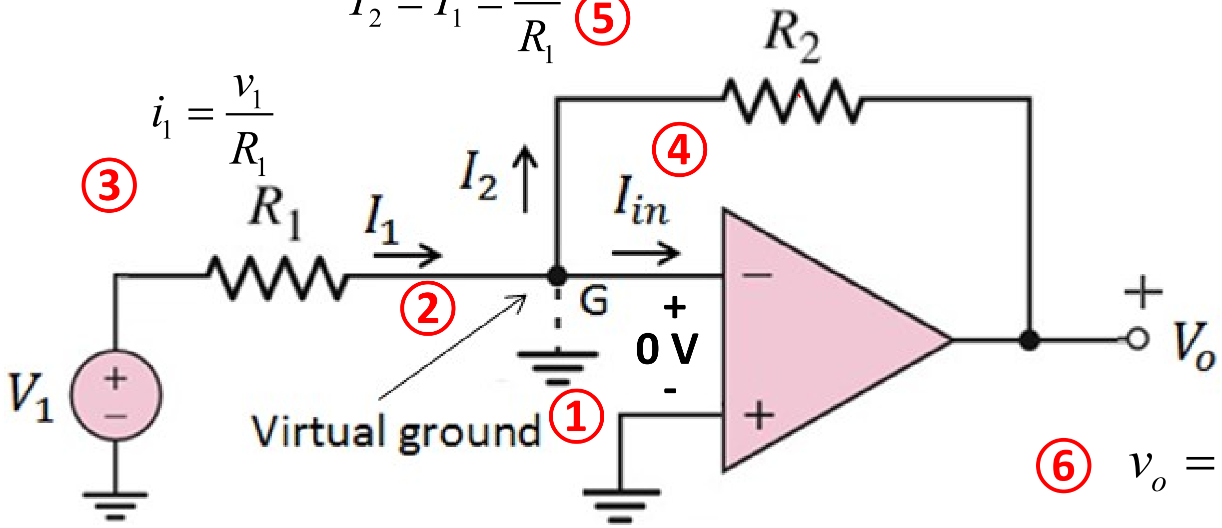
$$G = \frac{v_0}{v_1}$$

- Virtual short circuit between terminals 1 and 2 i.e., whatever voltage is at terminal 2 will automatically appear at terminal 1.

Output Voltage Inverting Op-amp

$$I_2 = I_1 = \frac{v_1}{R_1} \quad (5)$$

$$i_1 = \frac{v_1}{R_1} \quad (3)$$



$$(6) \quad v_o = 0 - \frac{v_1}{R_1} R_2$$

$$v_o = -\frac{R_2}{R_1} v_1$$

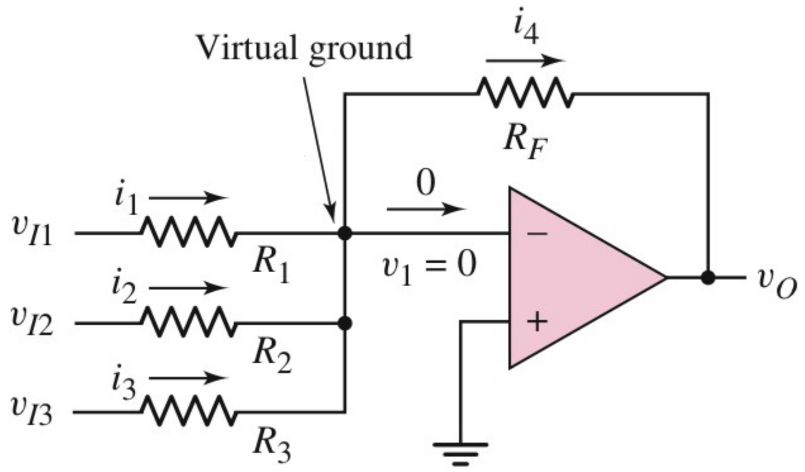
- Due to virtual ground at node 1,

$$i_1 = i_2$$

$$\frac{v_1 - 0}{R_1} = \frac{0 - v_0}{R_2}$$

$$v_0 = \frac{-R_2}{R_1} v_1$$

Weighted Summer Circuit



$$i_1 = \frac{v_1 - 0}{R_1}, i_2 = \frac{v_2 - 0}{R_2}, i_3 = \frac{v_3 - 0}{R_3}$$

$$i = i_1 + i_2 + i_3$$

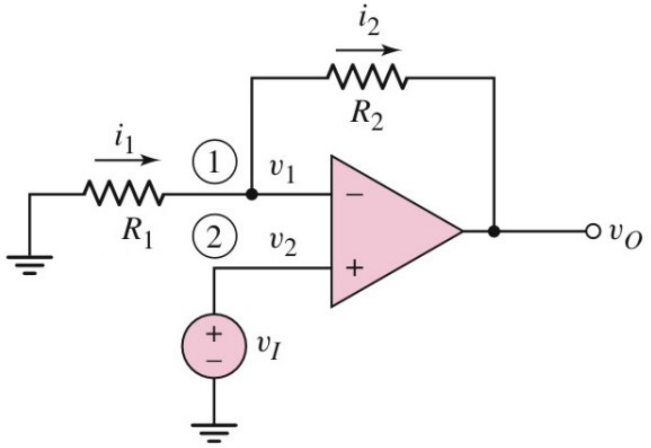
KCL
$$\frac{0 - v_o}{R_f} = \frac{v_1 - 0}{R_1} + \frac{v_2 - 0}{R_2} + \frac{v_3 - 0}{R_3}$$

$$v_o = -R_f\left(\frac{v_1}{R_1} + \frac{v_2}{R_2} + \frac{v_3}{R_3}\right)$$

When $v_1 = v_2 = \ldots v_n = v$

$$v_o = -\left(\frac{R_f}{R_1} + \frac{R_f}{R_2} + \frac{R_f}{R_3}\right)v$$

Non-inverting Op-amp



$$\frac{v_1}{R_1} = \frac{v_0 - v_1}{R_2}$$

On solving, $v_0 = \left(1 + \frac{R_2}{R_1}\right) v_1$

Differential Amplifier

- Differential amplifier accepts the difference signal from the input terminals and rejects the common signal from the input terminals
- The output voltage of an op-amp in terms of difference and common mode signal is

$$v_o = A_d v_{Id} + A_{cm} v_{Icm}$$

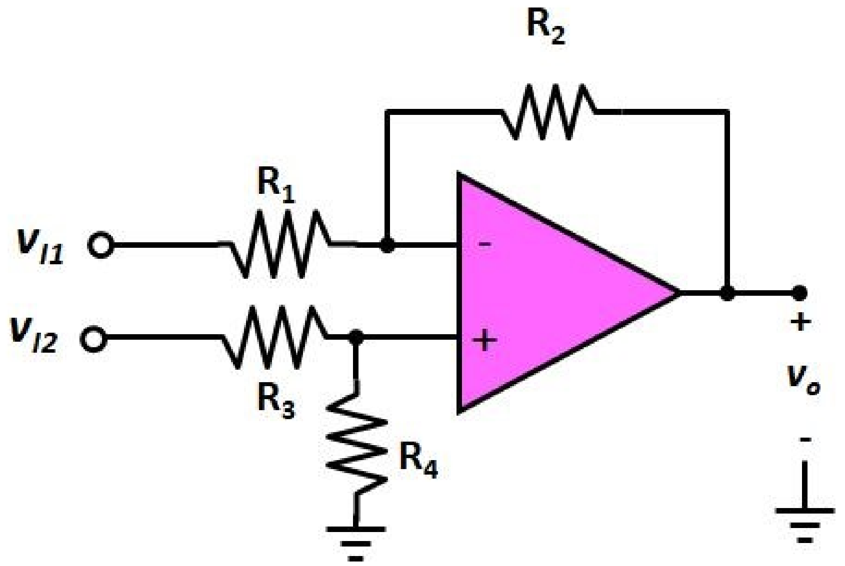
where A_d is the differential gain and A_{cm} is the common mode gain

- Differential amplifier efficacy is measured by the degree of rejection of common mode signals over differential signals
- This is quantified by the common-mode rejection ratio (CMMR) as

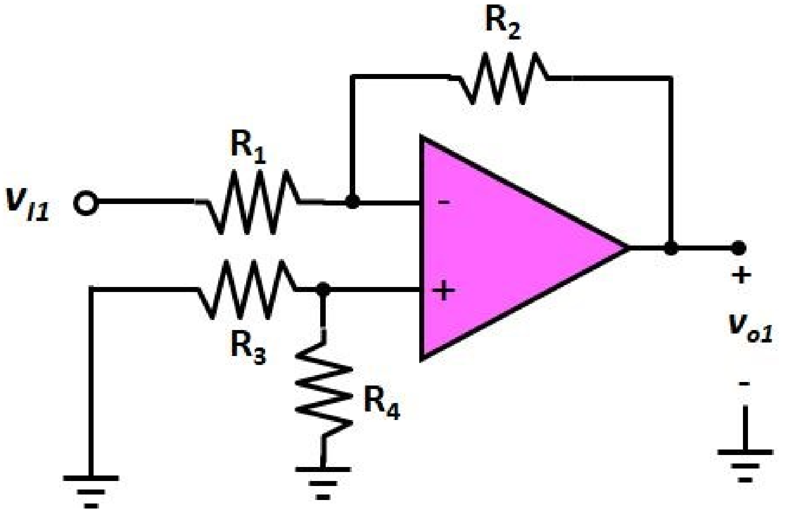
$$CMMR = 20\, log \left|\frac{A_d}{A_{cm}}\right|$$

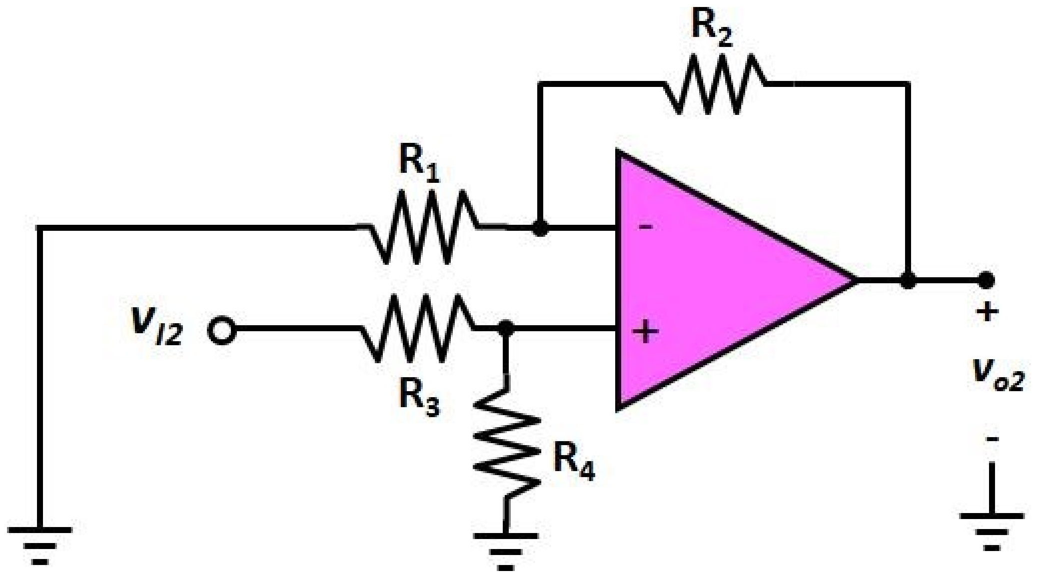
- Differential amplifiers are used in instrumentation.
- For example, a transducer differential output is very low and it is connected to a measurement instruments which rejects the interference signals relative to circuit ground.
- A differential amplifier amplifies the difference signal

Differential Amplifier

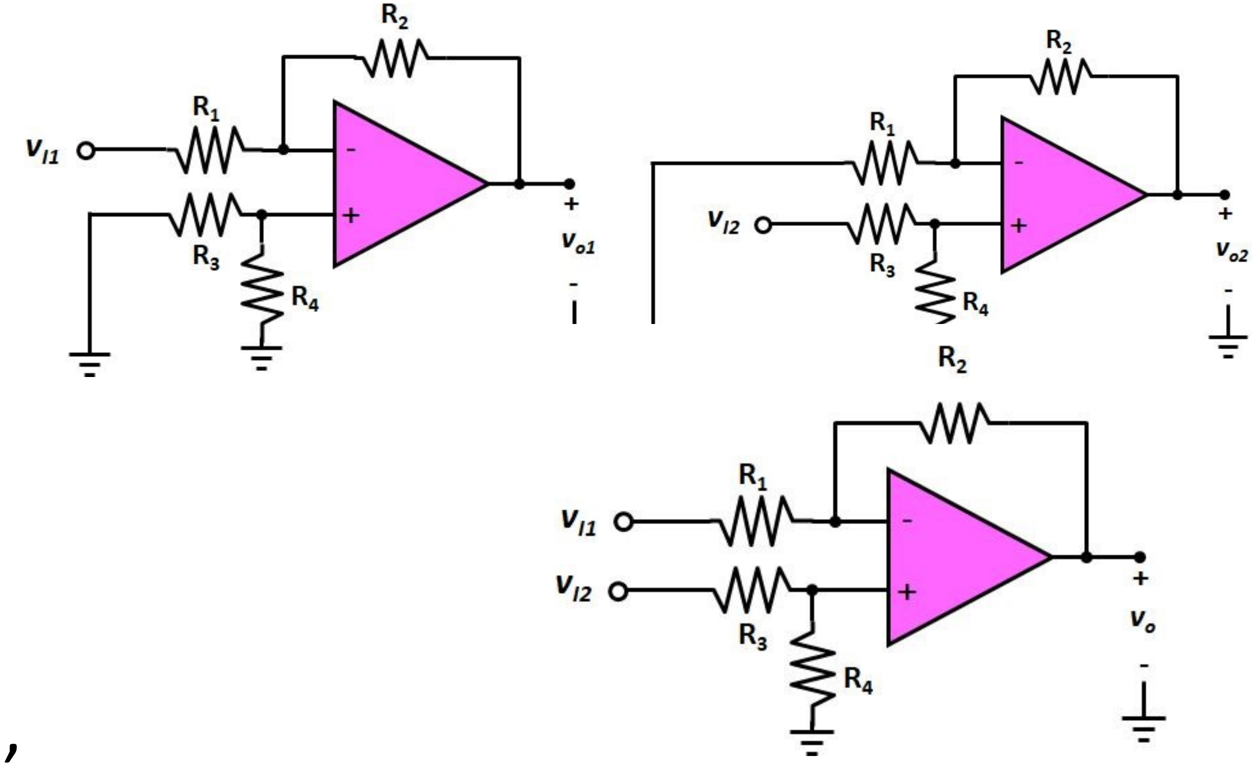


Using superposition theorem,





Differential Amplifier



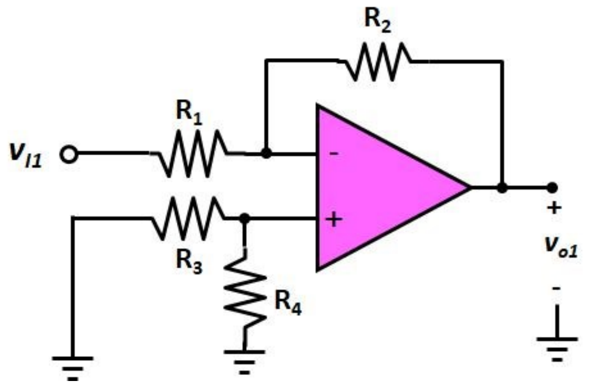
$$v_{o1} = -\frac{R_2}{R_1} v_{I1}$$

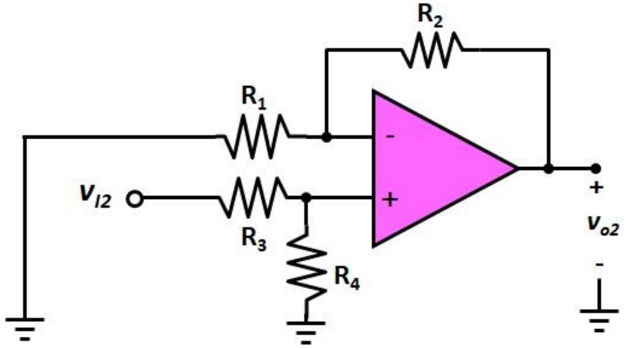
$$v_{o2} = v_{I2} \frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right)$$

- Using the Superposition principle,

$$v_o = \frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right) v_{I2} - \frac{R_2}{R_1} v_{I1}$$

Differential Amplifier

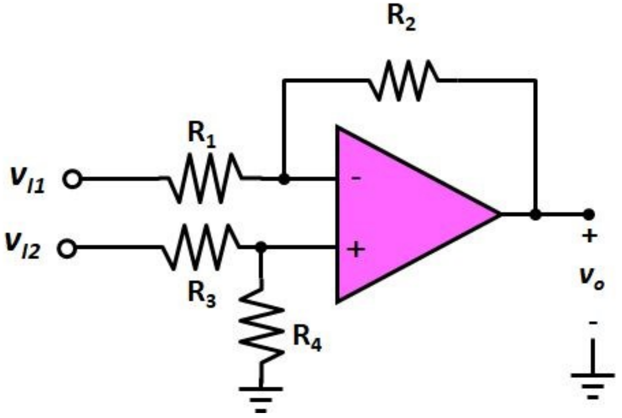




$$v_{o1} = -\frac{R_2}{R_1} v_{I1}$$

$$v_{o2} = v_{I2} \frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right)$$

Let $\frac{R_4}{R_3} = \frac{R_2}{R_1}$ $\quad v_{o2} = v_{I2} \frac{R_4}{R_3 + R_4}\left(1 + \frac{R_2}{R_1}\right) = \frac{R_2}{R_1} v_{I2}$



- Using the Superposition principle,

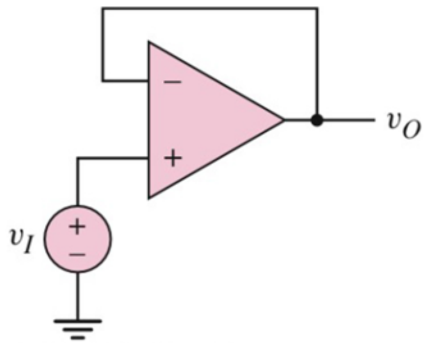
$$v_o = \frac{R_2}{R_1}\left(v_{I2} - v_{I1}\right) = \frac{R_2}{R_1} v_{Id} = A_d v_{Id}$$

Here, $A_d = \frac{R_2}{R_1}$

Op-amp Voltage Follower

- Op-amp has very high input impedance and low output impedance. This property can be used for using an op-amp as a buffer amplifier to connect a source with high impedance to a load with low impedance
- Buffer amplifier is not used to provide any voltage gain
- Buffer amplifier is used as a power amplifier or

  impedance transformer
- For buffer amplifier, R_2=0 and R_1=∞ and $v_o = v_i$
- Due to unity gain, the output voltage follows the input.
- That's why it is called a voltage follower



A voltage follower circuit/Buffer amplifier

Integrator

When the feedback resistor of an inverter circuit is replaced by a capacitor the circuit is works as an integrator circuit - causing the output to respond to changes in the input voltage over time

Applying KCL at node G

$$I_S = I_{in} + I_C$$

Since R_{in} = ∞ $I_{in} = 0$

Since node G is at virtual ground,

$$I_S = I_C = \frac{V_s}{R_1}$$

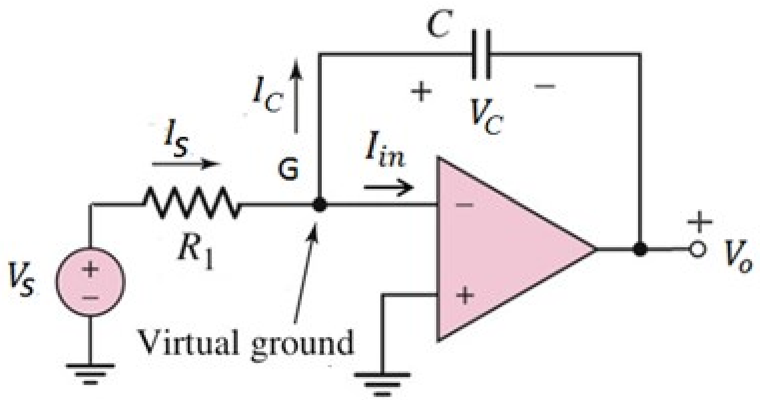
The voltage across the capacitor V_C is given by

$$V_C = \frac{Q}{C} = -V_o$$

The charge in the capacitor Q is given by

$$Q = \int I_s dt = \int \frac{V_s}{R_1} dt$$

Output voltage, $V_o = \frac{-1}{R_1 C} \int V_S \, dt$



Integrator circuit

Output voltage v_o is given by

$$v_o = \int I_s dt = \frac{-1}{R_1 C} \int V_s dt$$

If the capacitor is charged is initially charged to a voltage V_x,

$$v_o = V_x - \frac{1}{R_1 C} \int V_s dt$$

Differentiator

When the inverting input terminal resistor of an op-amp inverter circuit is replaced by a capacitor, the circuit works as a differentiator circuit.

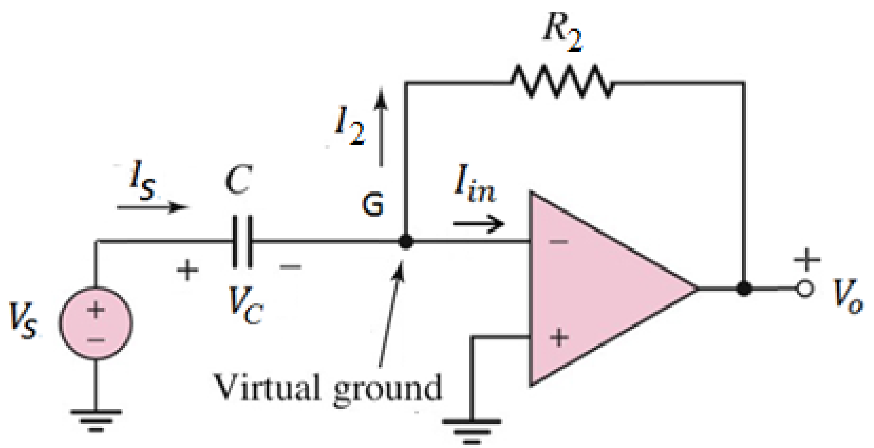
Applying KCL at node point G

$$I_S - I_{in} - I_2 = 0$$

$I_{in} = 0$ since, $R_{in} = \infty$

Therefore, $I_2 = I_S$

Since G point is a virtual ground



Differentiator circuit

Voltage across the capacitor,

$$V_C = \frac{Q}{C} = V_S$$

Because $Q = CV_S$

Or, $$I_S = \frac{dQ}{dt} = C\frac{dV_S}{dt}$$

Again, the output voltage,

$$V_o = -I_2R_2 = -I_SR_2$$

Therefore, $$V_o = -CR_2\frac{dV_S}{dt}$$