Signal Conditioning

ENGG 6150: Bio-Instrumentation

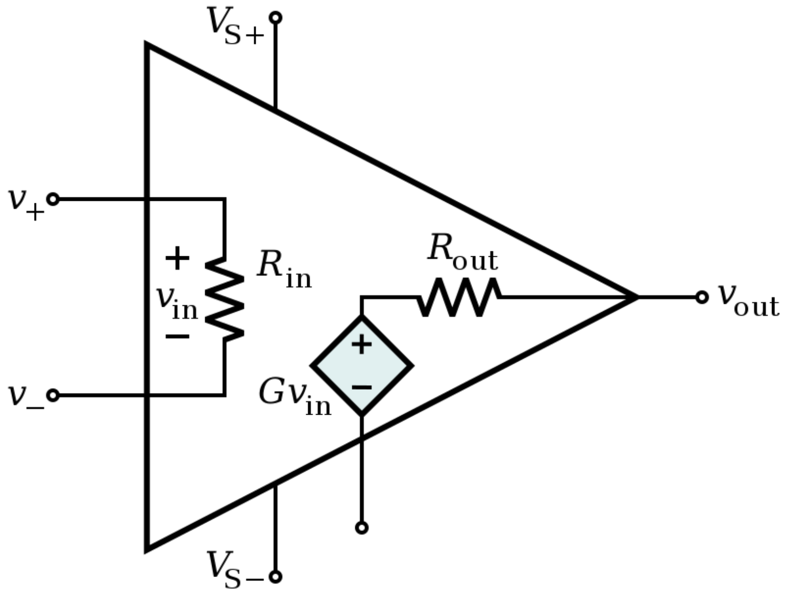
Signal Conditioning

- Operational amplifier
- Differential amplifier
- Instrumentational amplifier
- Common Mode Rejection Ratio (CMRR)

Operational Amplifiers
(OP – AMP)

What is an Operational Amplifiers

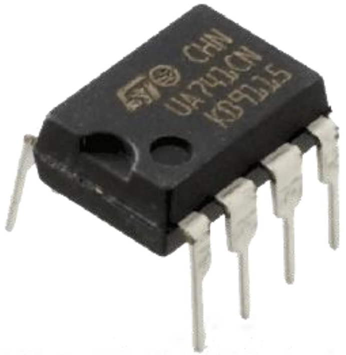
It is a 3-terminal electronic device that has a very high gain which can be used to amplify the difference between two input voltages.

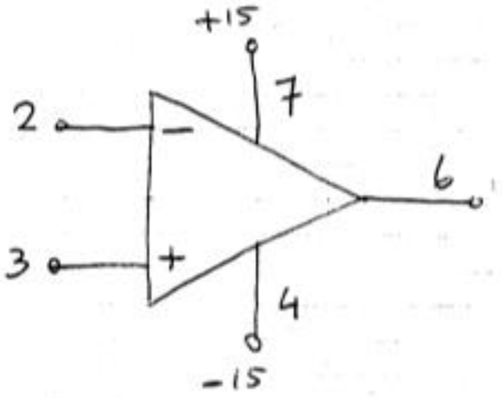


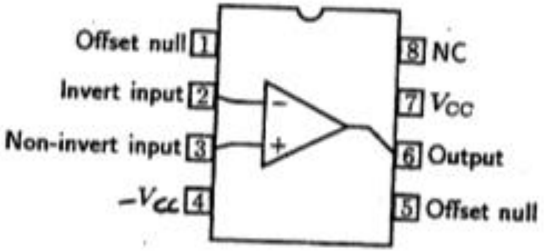
So, $V_{out} = G(V_+ - V_-) = GV_{in}$

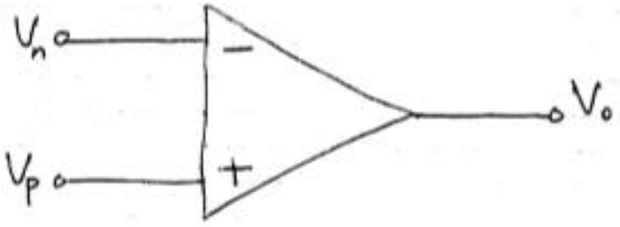
Pin Connection and Symbol for OP AMP

- All OP AMPs have at least five terminals as follows:
  - Inverting input
  - Non-Inverting input
  - Output terminal
  - +ve bias supply
  - -ve bias supply



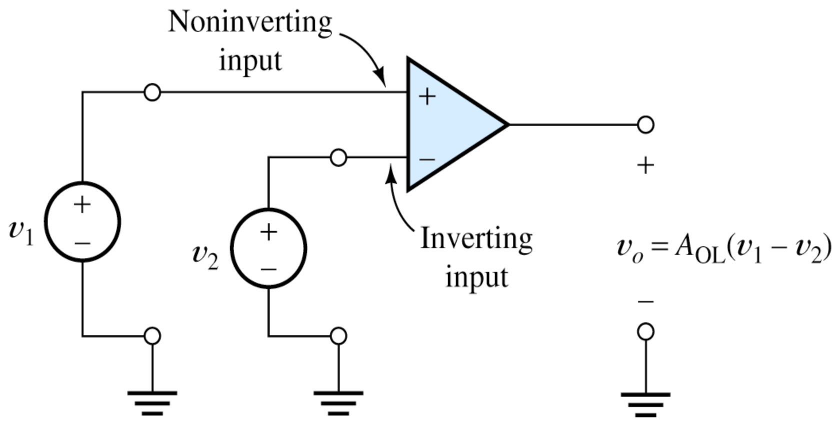






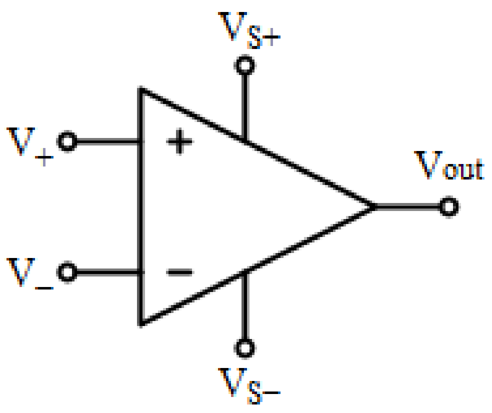
Characteristics of Ideal Op Amps

- Infinite gain for the differential input signal
- Infinite input impedances
- Zero output impedance
- Infinite bandwidth



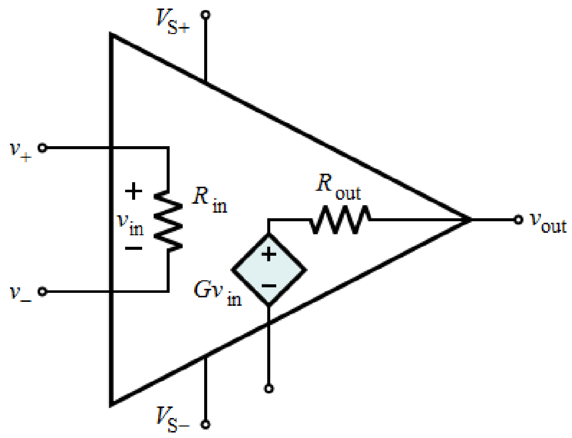
Ideal versus Real Op-Amps

Parameter	Ideal Op-Amp	Real Op-Amp
Differential Voltage Gain	∞	10^5 - 10^9
Gain Bandwidth Product (Hz)	∞	1-20 MHz
Input Resistance (R)	∞	10^6 - 10^{12} Ω
Output Resistance (R)	0	100 - 1000 Ω



Ideal

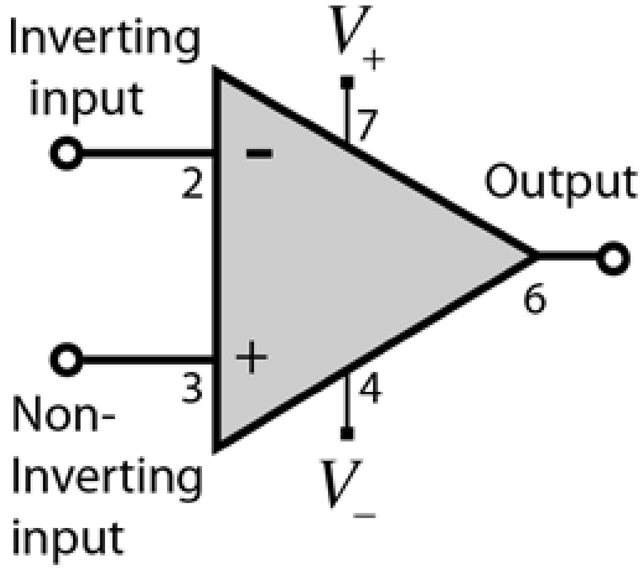
Real



http://hyperphysics.phy-astr.gsu.edu/hbase/electronic/opamp.html#c4

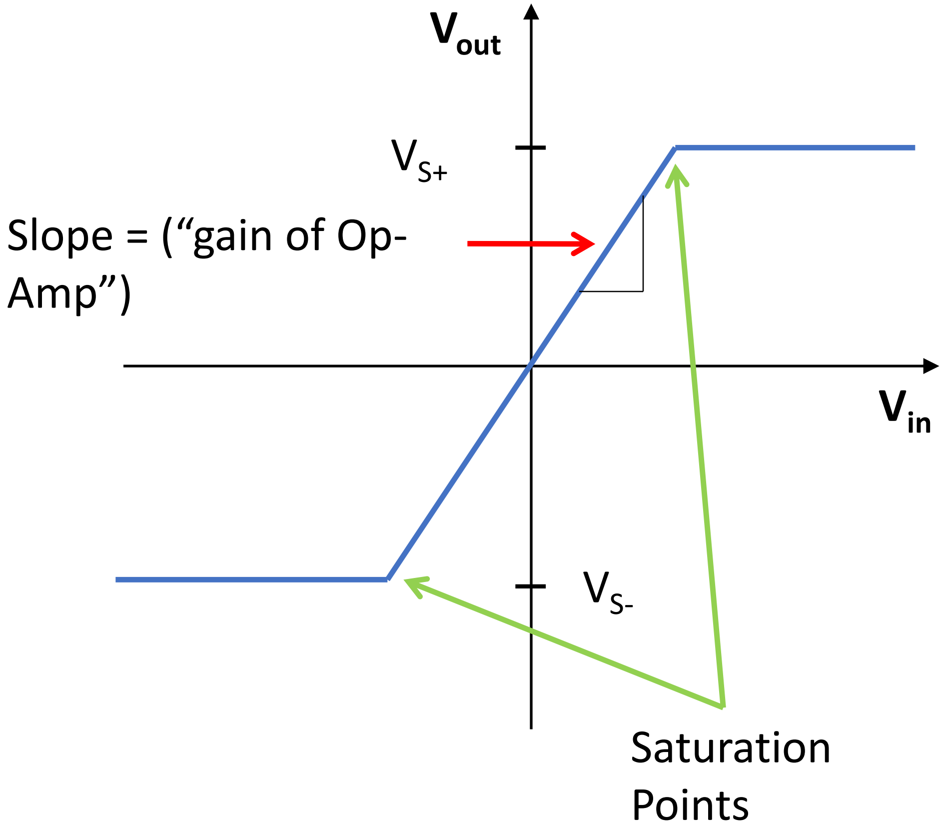
Op Amps Properties

- The input currents are equal to zero, i.e. input currents to terminals 2 and 3
- The voltages at terminals 2 and 3 are equal.

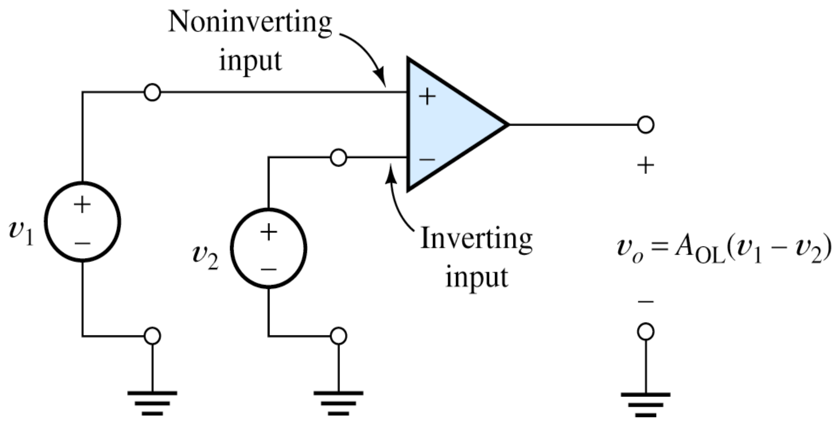


Saturation

Saturation is caused by increasing/decreasing the input voltage to cause the output voltage to equal the power supply's voltage*



So, using the OP-AMP in open loop configuration is useless, and we need to use it in a different configuration



1-Inverting Amplifier

Find the voltage gain for this OP AMP circuit

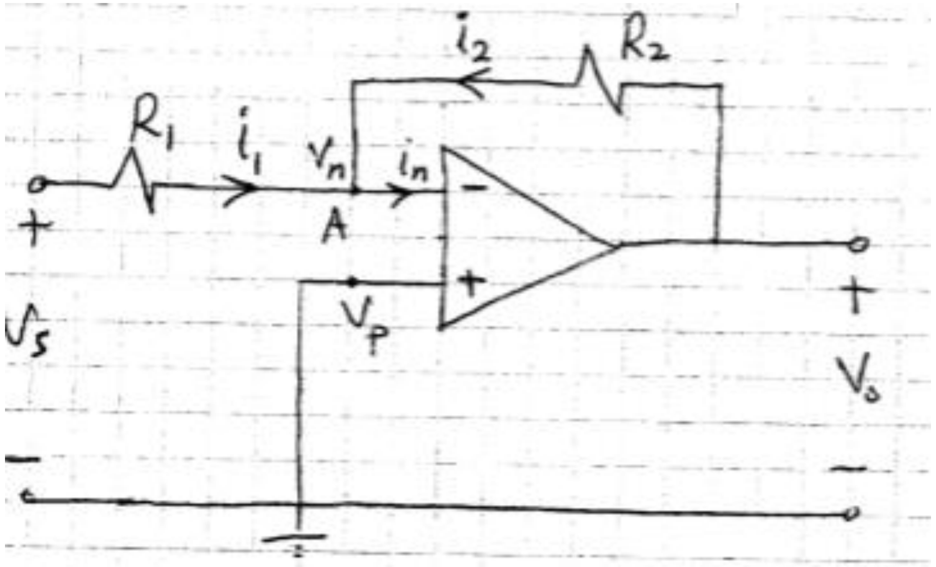
apply KCL to node A

$$\frac{V_s - V_n}{R_1} + \frac{V_o - V_n}{R_2} = 0$$

Now $\left.\begin{array}{l} V_n = V_p = 0 \\ i_n = 0 \end{array}\right\}$ Op-amp rules

i.e $\frac{V_s}{R_1} = \frac{-V_o}{R_2}$

$$\frac{V_o}{V_s} = -\frac{R_2}{R_1}$$

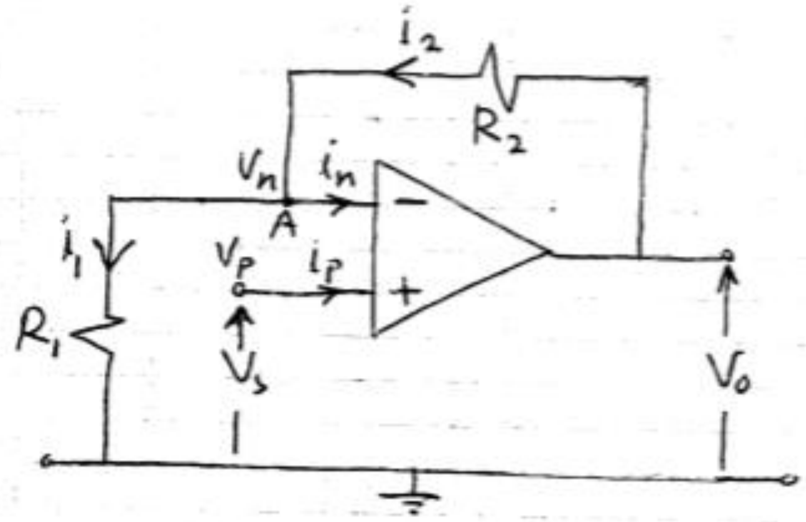


2- Non-Inverting Amplifier

Find the voltage gain for this OP AMP circuit

$$i_n + i_1 = i_2$$

$$i_n + \frac{V_n}{R_1} = \frac{V_o - V_n}{R_2}$$



Now $\left.\begin{array}{l} V_n = V_p = V_s \\ i_n = 0 \end{array}\right\}$ Op-amp rules

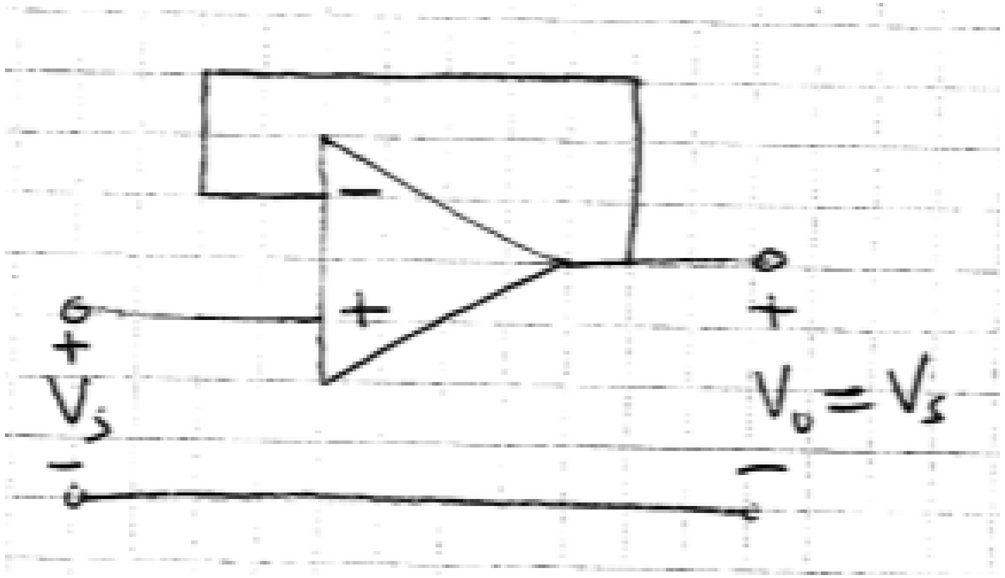
$$\therefore \quad \frac{V_s}{R_1} = \frac{V_o - V_s}{R_2}$$

or $$\frac{V_o}{V_s} = \frac{R_1 + R_2}{R_1} = 1 + \frac{R_2}{R_1}$$

3- Voltage follower

When R2 = 0, as shown below, then:

$V_0/V_s = 1$

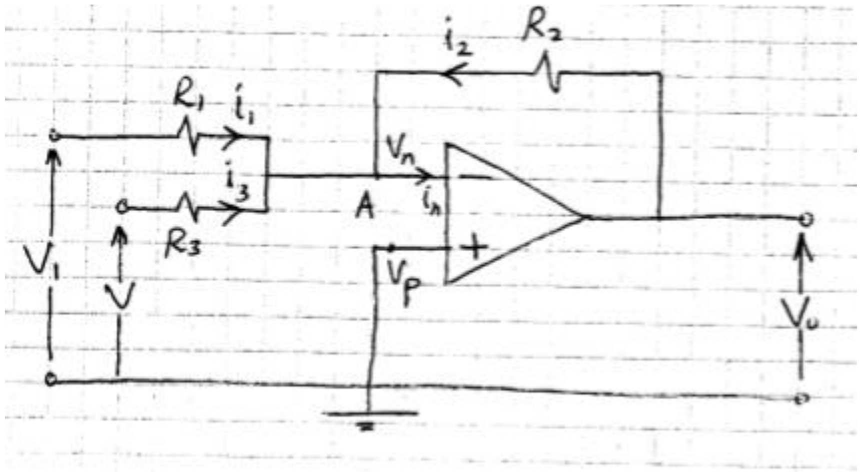


4- Adder Inverter

Find the voltage gain for this OP AMP circuit

KCL at node A :

$$i_1 + i_2 + i_3 = i_n$$



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

$i_n = 0$

$V_n = V_p = 0$

$$\frac{V_1}{R_1} + \frac{V_o}{R_2} + \frac{V_2}{R_3} = 0$$

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

for $R_1 = R_2 = R_3$

$$V_o = -(V_1 + V_2)$$

Examples

<u>Example 1:</u> For the ideal op amp shown, what should be the value of resistor Rf to obtain a gain of 5?

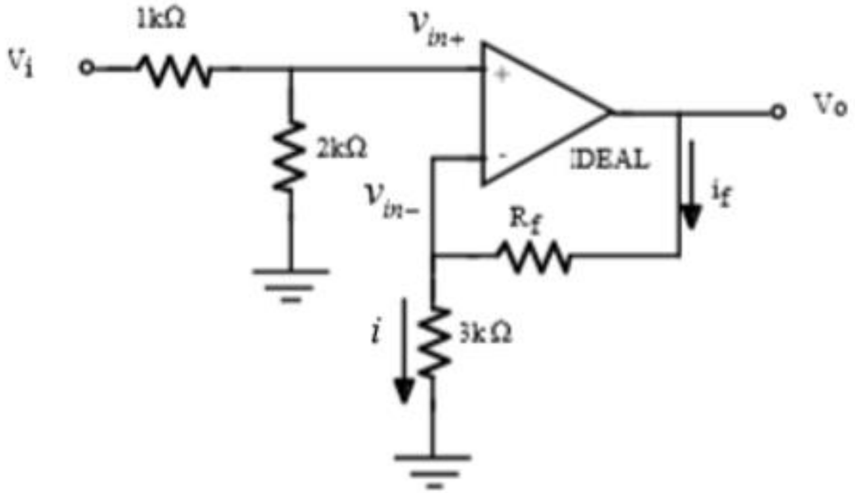
By voltage division, $v_{in+} = v_i\left(\frac{2k\Omega}{3k\Omega}\right) = \frac{2}{3}v_i$

By the virtual short circuit, $v_{in-} = v_{in+} = \frac{2}{3}v_i$

$$i = \frac{v_{in-}}{3k\Omega} = \frac{\frac{2}{3}v_i}{3k\Omega}$$

Since the op amp draws no current, i_f=i

$$\frac{v_o - v_{in-}}{R_f} = \frac{\frac{2}{3}v_i}{3k\Omega}$$



Examples

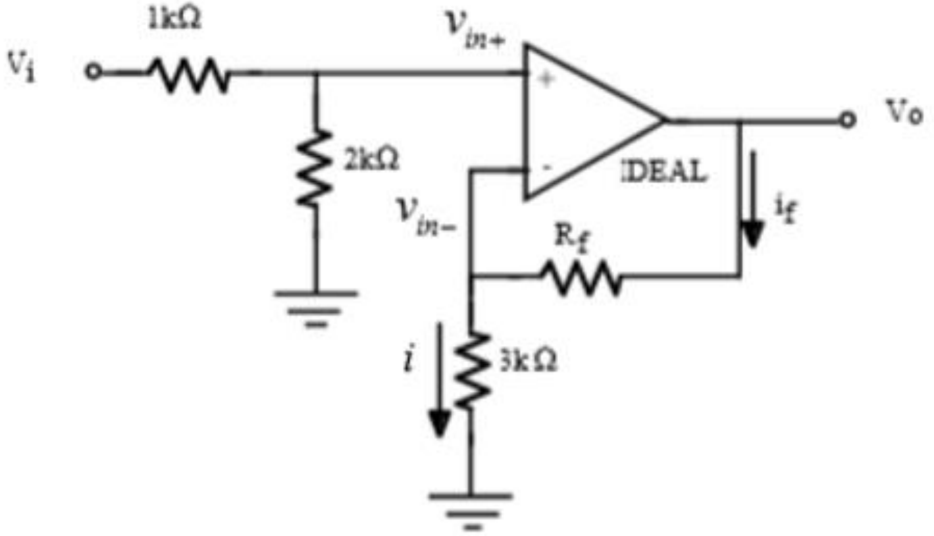
Example 1:, continue

But, $v_o = 5v_i$.

$$\frac{5v_i - \frac{2}{3}v_i}{R_f} = \frac{\frac{2}{3}v_i}{3k\Omega}$$

$$\frac{\frac{13}{3}}{R_f} = \frac{\frac{2}{3}}{3k\Omega}$$

R_f=19.5 kΩ

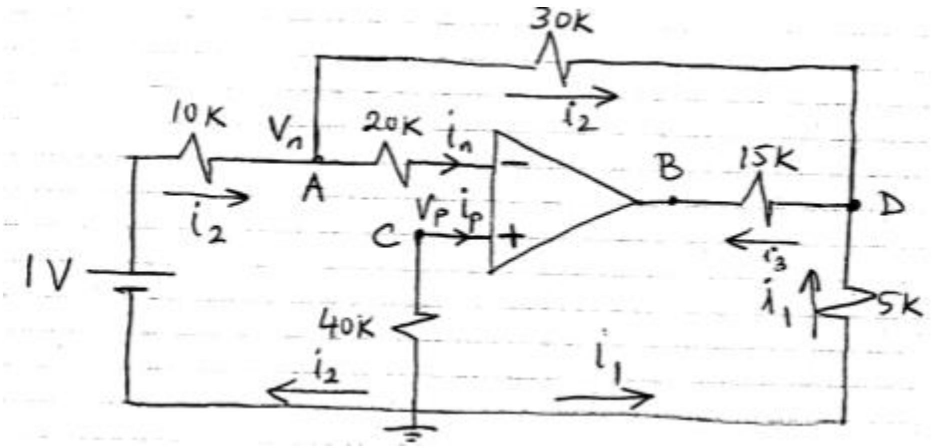


Examples

Example 2: Find the power dissipated by all resistors and the 1-V supply

apply KCL at A

$$\frac{1-V_n}{10\times10^3} + \frac{V_D - V_n}{30\times10^3} = i_n$$



But $\quad i_n = i_p = 0 \quad$ (op-amp rule)

$\therefore V_p = 0 \quad$ (since $i_p = 0$)

$\therefore V_n = V_p = 0 \quad$ (Op-amp)

$$\frac{1}{10^4} + \frac{V_D}{3\times10^4} = 0$$

$\Rightarrow V_D = -3V$

Examples

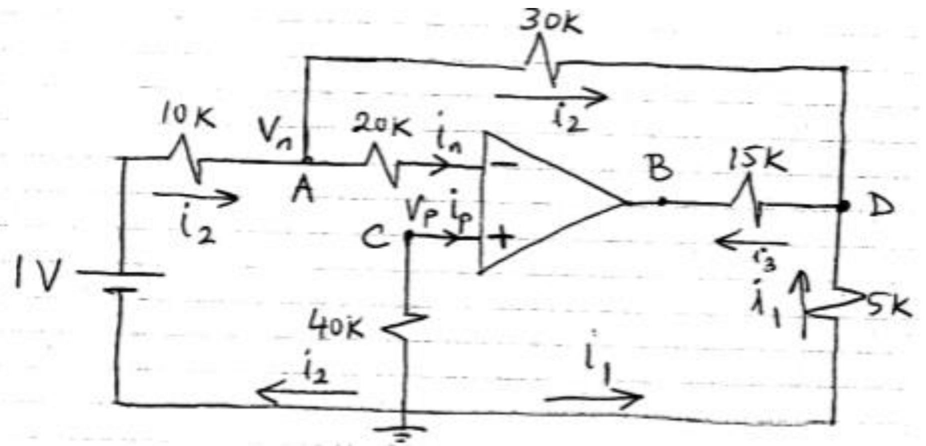
1) Solution - Continue

$$i_1 = \frac{0 - V_D}{5 \times 10^3} = \underline{\underline{600\ \mu A}}$$

and

$$i_2 = \frac{V_n - V_D}{30 \times 10^3} = \frac{3}{30 \times 10^3}\ A$$

$$= \underline{\underline{100\ \mu A}}$$



Apply KCL at D.

$$i_3 = i_1 + i_2 = \underline{700\ \mu A}$$

Power dissipated in 15K resistor =

$$= (i_3)^2 (15 \times 10^3)$$

$$= 49 \times 15 \times 10^{-5}$$

$$= 7.35\ \underline{mW}$$

Examples

1) Solution - Continue

also

$$\frac{V_D - V_B}{15\times10^3} = i_3$$

$$\therefore \quad V_B = \underline{\underline{-13.5\,V}}$$

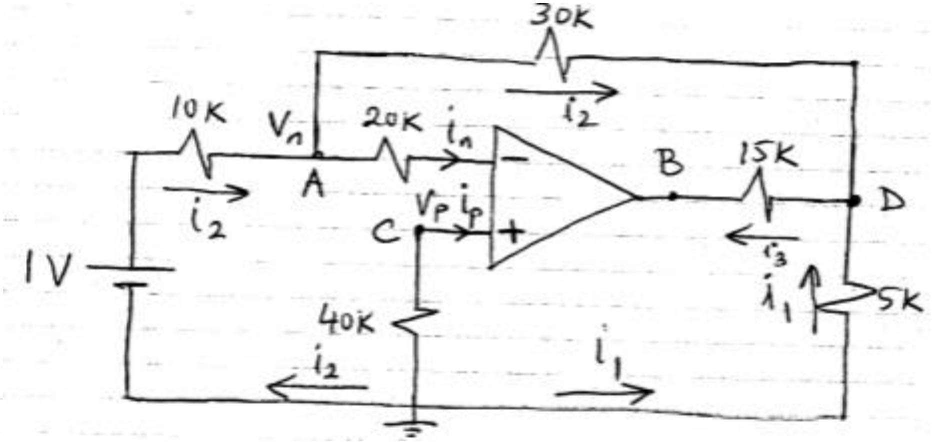
power in 5k resistor $= (i_1)^2(5\times10^3) = 1.8$ mW

" " 30k " $= (i_2)^2(30\times10^3) = 0.3$ mW

" " 10K " $= (i_2)^2(10\times10^3) = 0.1$ mW

" " 20K " $= 0 \quad (i_n = 0)$

" " 40K " $= 0 \quad (i_p = 0)$



$\therefore$ Total power dissipated in resistors $= \underline{9.55\text{ mW}}$

power from 1V battery $= (1)(i_2)$

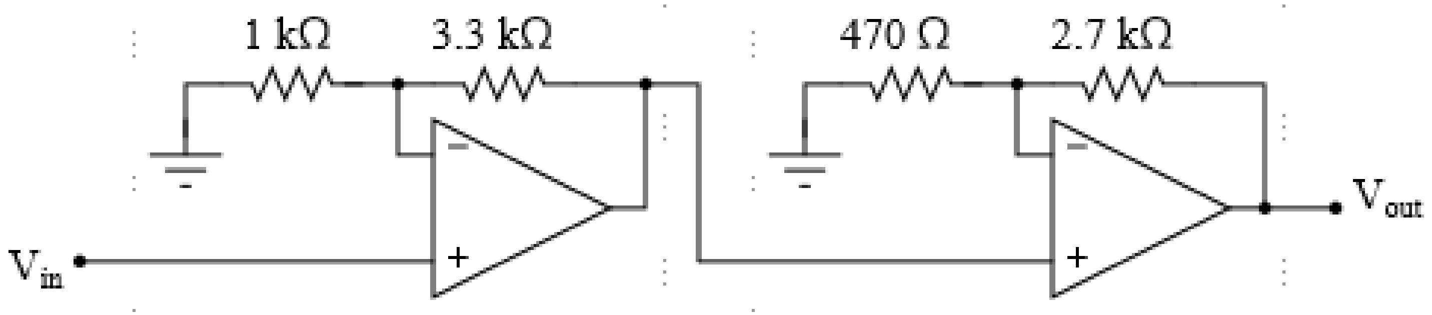
$= \underline{0.1\text{ mW}}$

The difference between power supplied and consumed will come from the biasing voltage

Examples

Example 3

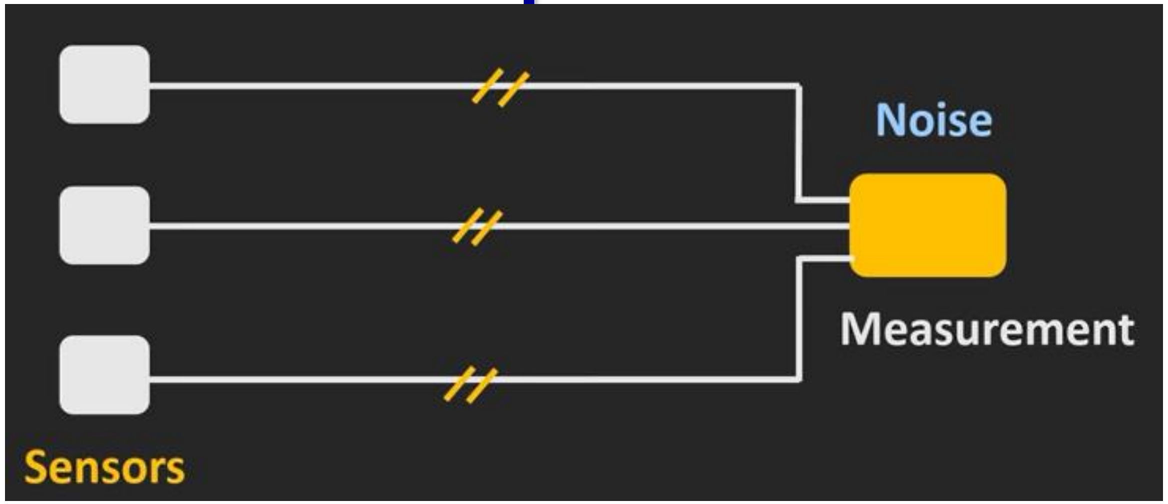
Calculate the output voltage in terms of the input voltage of the following multi-stage OP-AMP



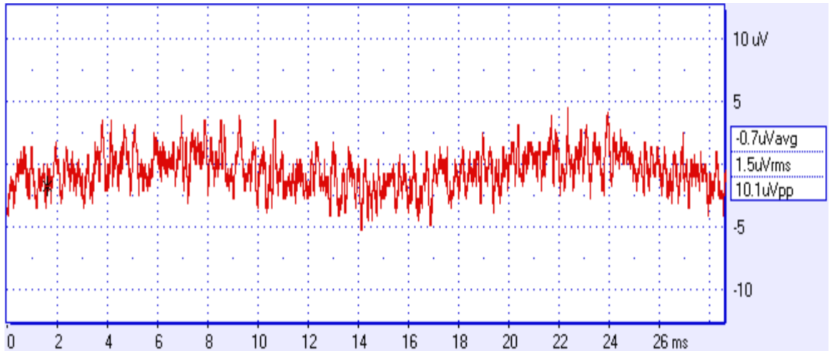
$$V_{out} = \left(1 + \frac{3.3}{1}\right) \times \left(1 + \frac{2.7}{0.47}\right) V_{in} = 29V_{in}$$

Differential Amplifiers

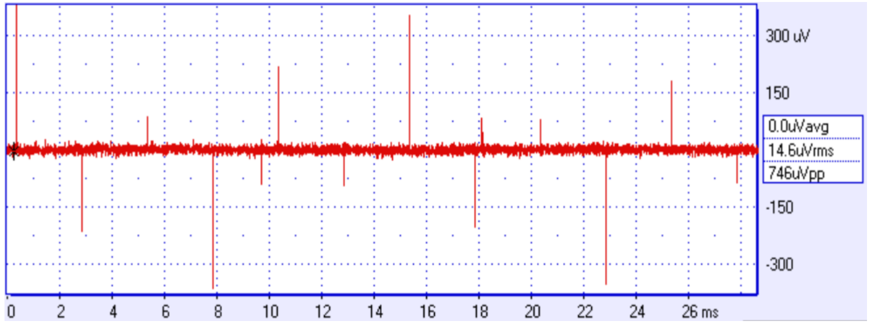
Why we need differential amplifier



In many applications the sensor location is far away from the instrument, so noise will be collected from the sensor.



50/60 Hz coupling



RF coupling

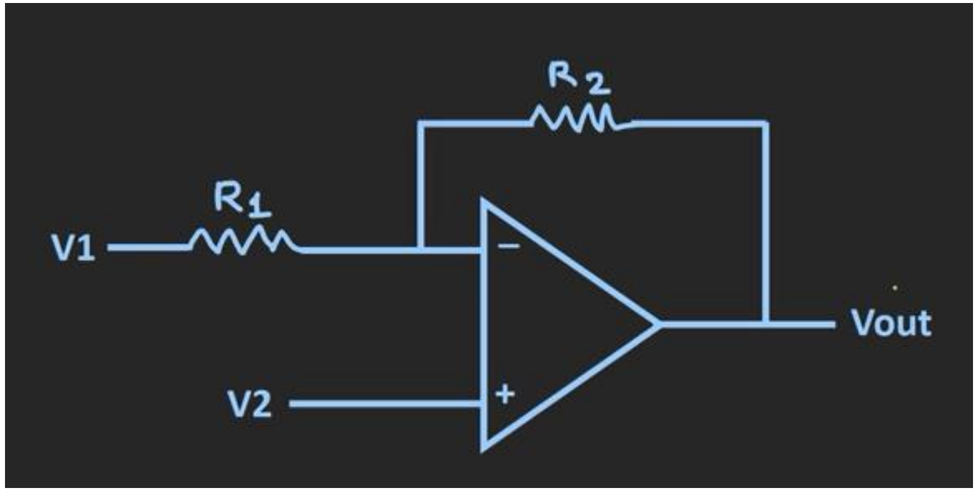
Why we need differential amplifier

- So, we need an amplifier that amplifies the difference between two input voltages hence it will suppress any voltage common to the two inputs.

- Differential amplifiers are often used to null out noise or bias-voltages that appear at both inputs.

- To understand the analysis of the Op-AMP in differential circuit configuration, we will use the superposition theory.

Differential Amplifier

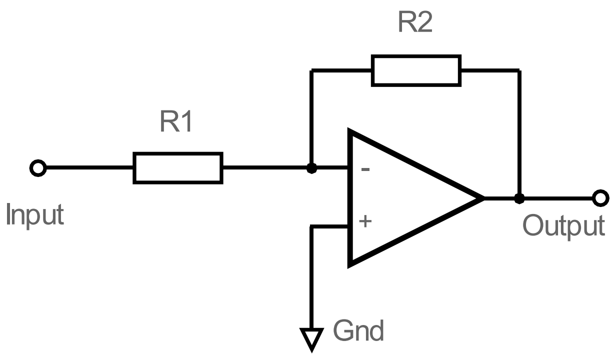


- Assume we have this configuration where we have inputs to each terminal.

- We will analyze the circuit assuming one input at a time.

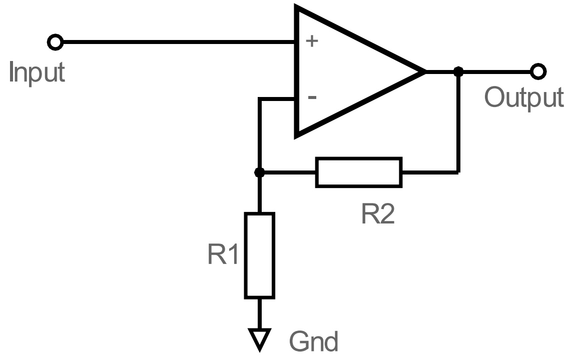
Differential Amplifier

- So first we will consider inverting circuit alone.



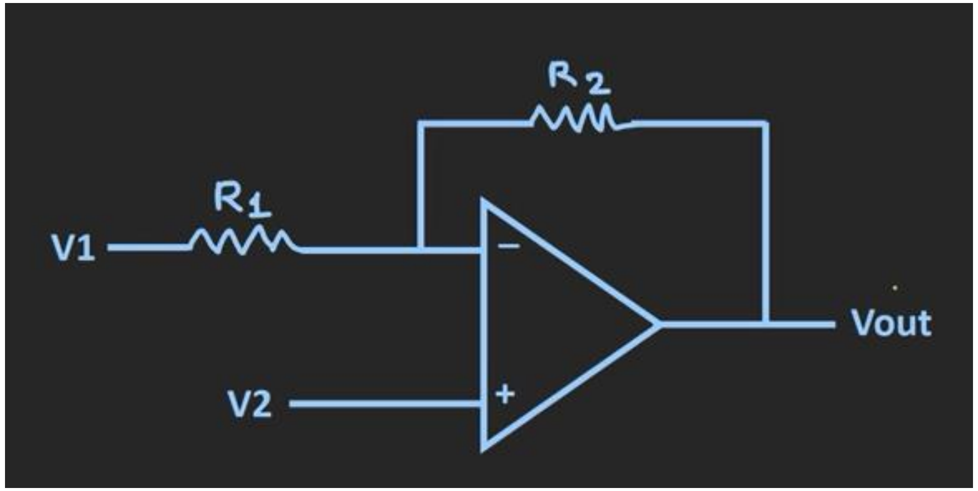
$$V_{out1} = -\frac{R_2}{R_1}V1$$

- Then we will consider the non-inverting circuit alone.



$$V_{out2} = \left(1 + \frac{R_2}{R_1}\right)V2$$

Differential Amplifier



- Now, we will consider the two inputs together, hence:

$$V_{out} = V_{out1} + V_{out2} = -\frac{R_2}{R_1}V1 + \left(1 + \frac{R_2}{R_1}\right)V2$$

- However, we want the output to be in the following form:

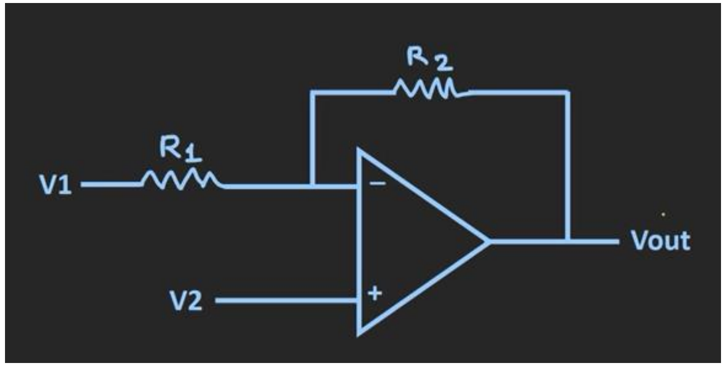
$$V_{out} = C \times (V2 - V1)$$

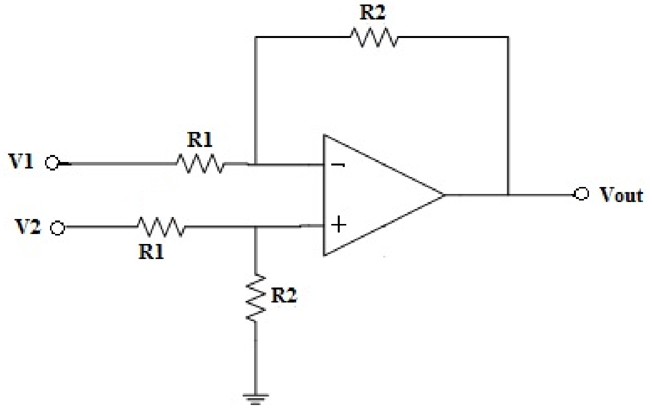
Differential Amplifier

- So, We want 1+R2/R1 to be equal to R2/R1

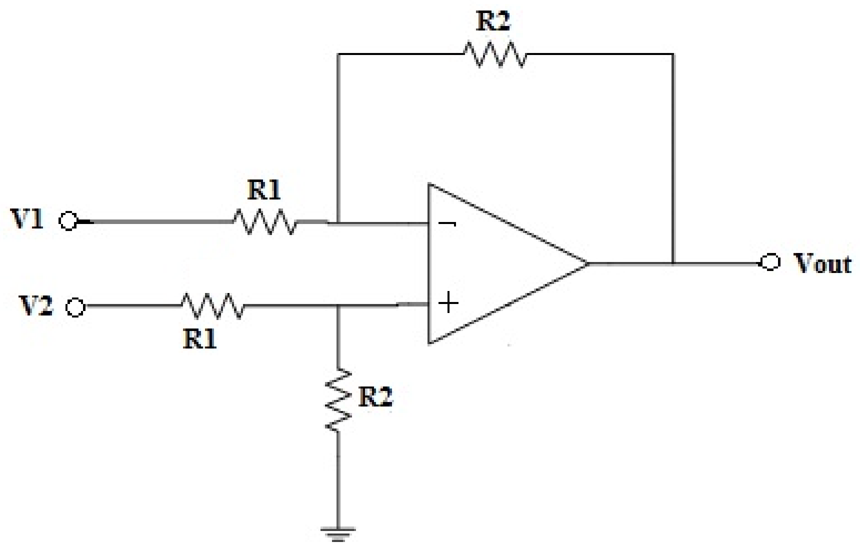
$$\left(1 + \frac{R_2}{R_1}\right) = \frac{R_1 + R_2}{R_1}$$

- So, if we multiply this term by R2/(R1+R2), then we will get R2/R1.
- To achieve this, then we need to have a voltage divider after V2 instead of applying it directly as follows:





Differential Amplifier



- Now, the output voltage will be:

$$V_{out} = V_{out1} + V_{out2} = -\frac{R_2}{R_1}V1 + \frac{R_2}{R_1}V2$$

$$V_{out} = \frac{R_2}{R_1}(V2 - V1)$$

Differential Amplifier

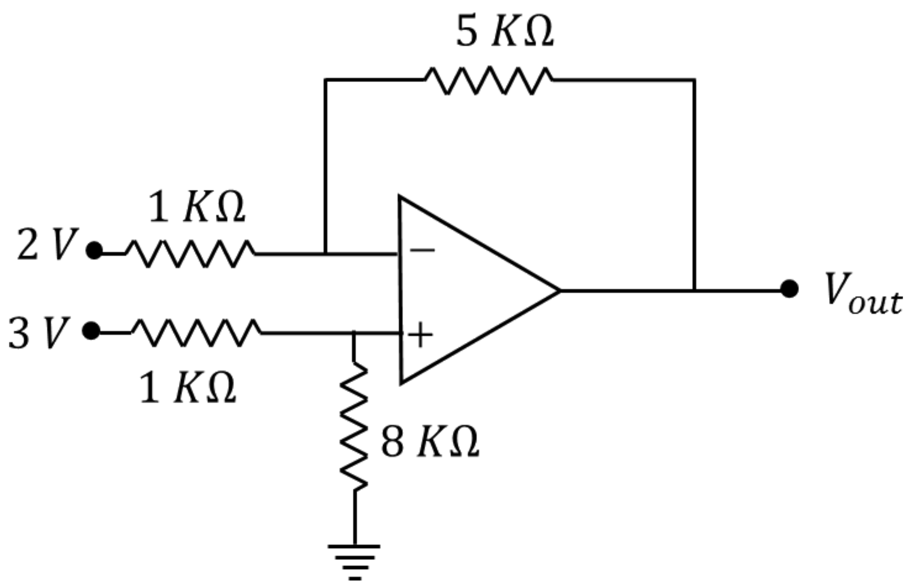
Example 5

Find the output voltage for the following amplifier.

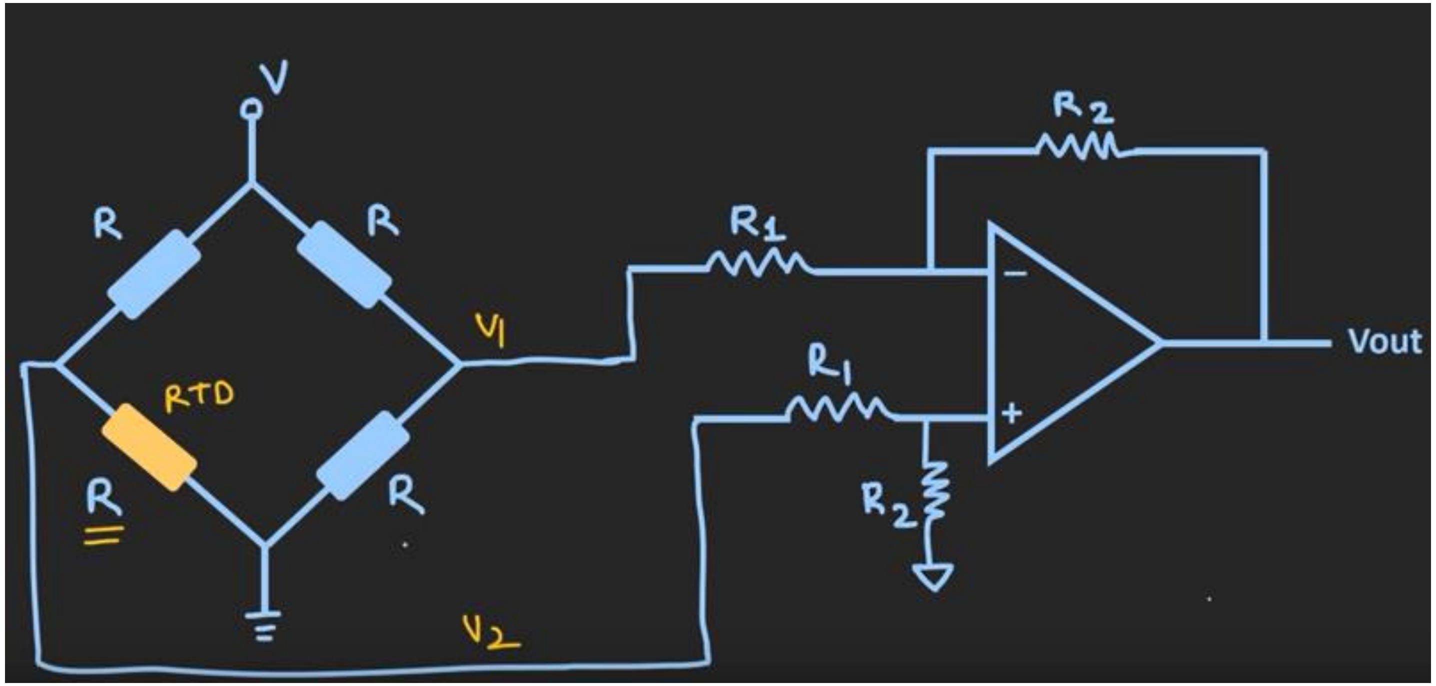
$$V_{out1} = -\frac{5}{1} \times 2 = -10V$$

$$V_{out2} = \left(1 + \frac{5}{1}\right)(6)\left(\frac{8}{8+1}\right) \times 3 = 16V$$

Vout = -10 + 16 = 6V



Differential Amplifier

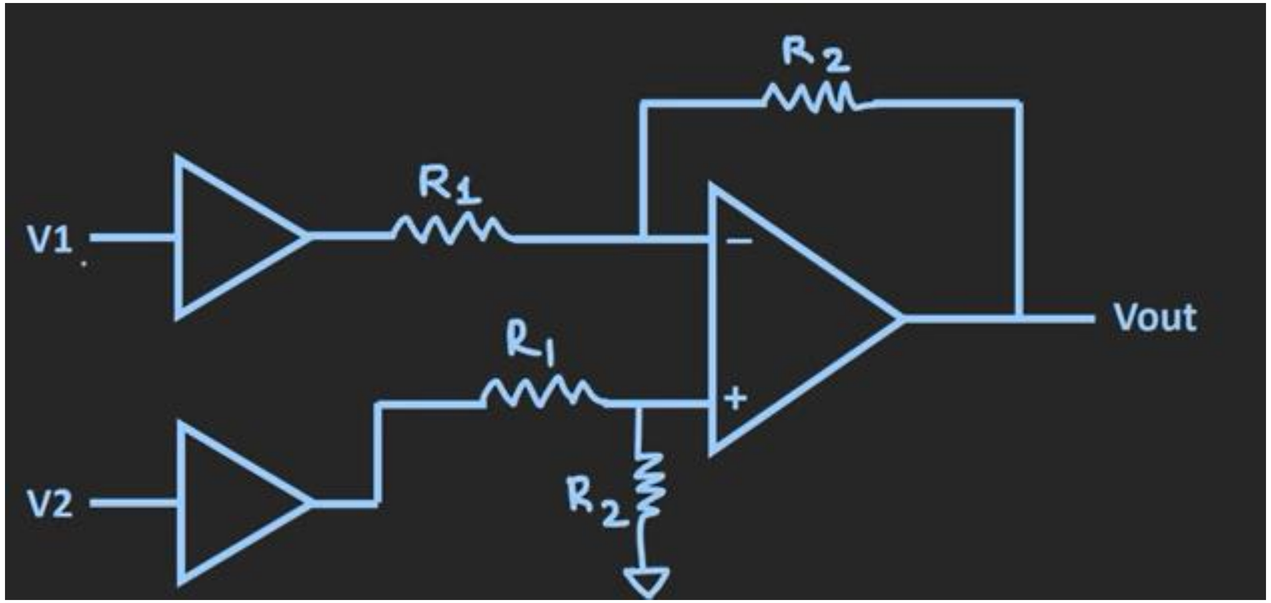


One application of the differential amplifier is to amplify the difference between the output terminals of the bridge.

HOWEVER, the main disadvantage of this configuration is that the input impedance is very small.

Differential Amplifier

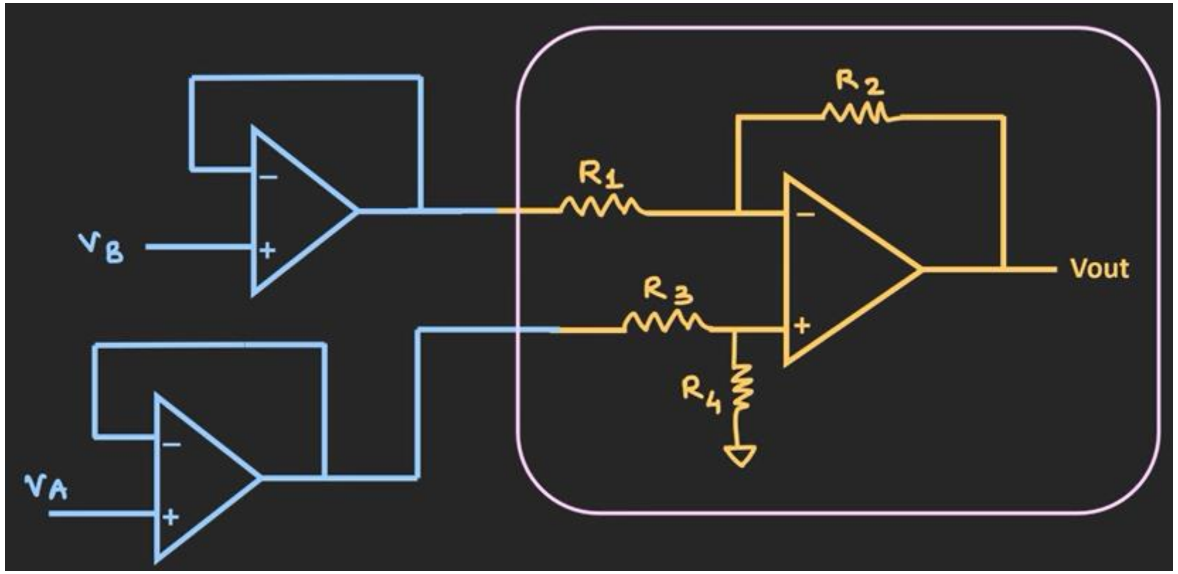
To get rid of this problem, we will apply a buffer before each input as follows:

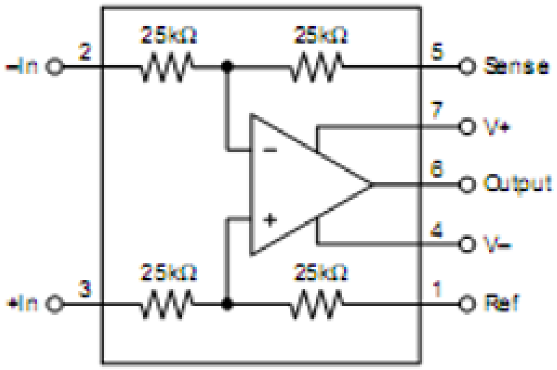


This will lead us to the instrumentation amplifier

Instrumentational Amplifiers

Instrumentational Amplifier

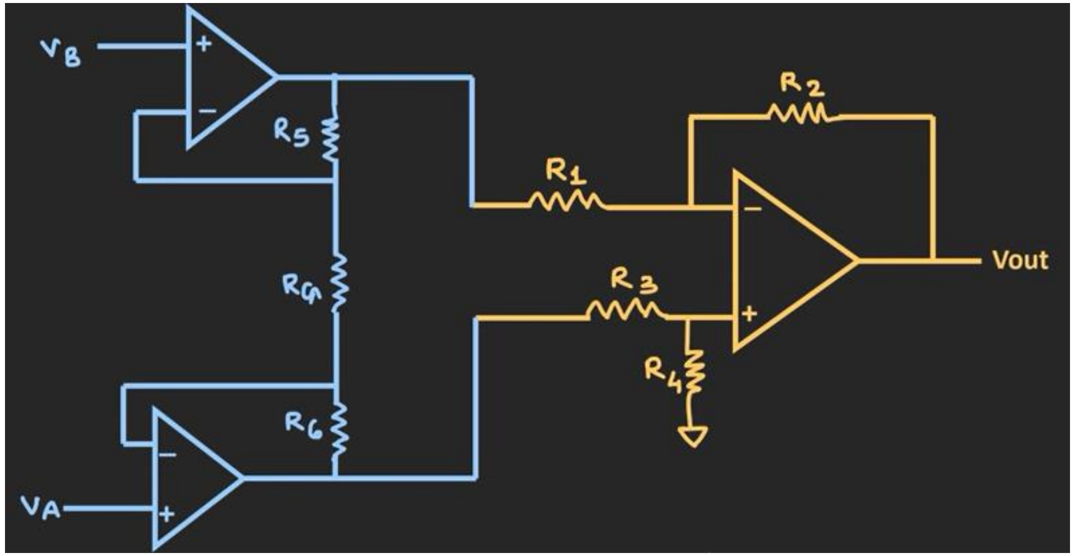


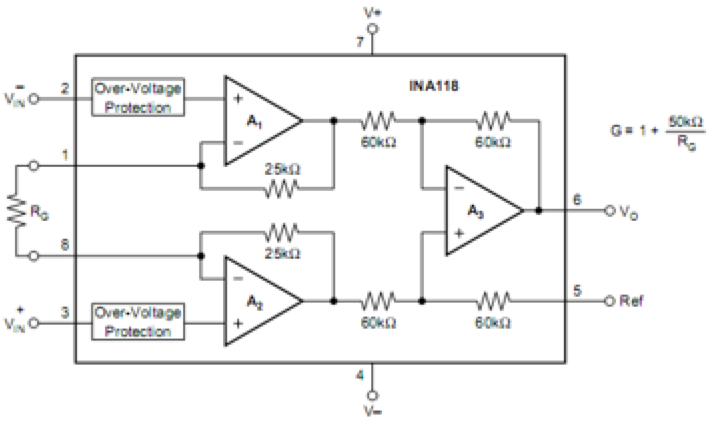


- The previous configuration can be implemented by having a voltage follower (previously discussed).

- However, this configuration will have fixed gain because all resistors will be integrated with the OP-AMP.

Instrumentational Amplifier





- This problem can be solved by having the following configuration which is called instrumentational amplifier.
- Except for RG, all resistors are fabricated internally.

Instrumentational Amplifier

$$V_{out} = \frac{R_2}{R_1}(V_A' - V_B')$$

Provided that R2/R1 = R4/R3

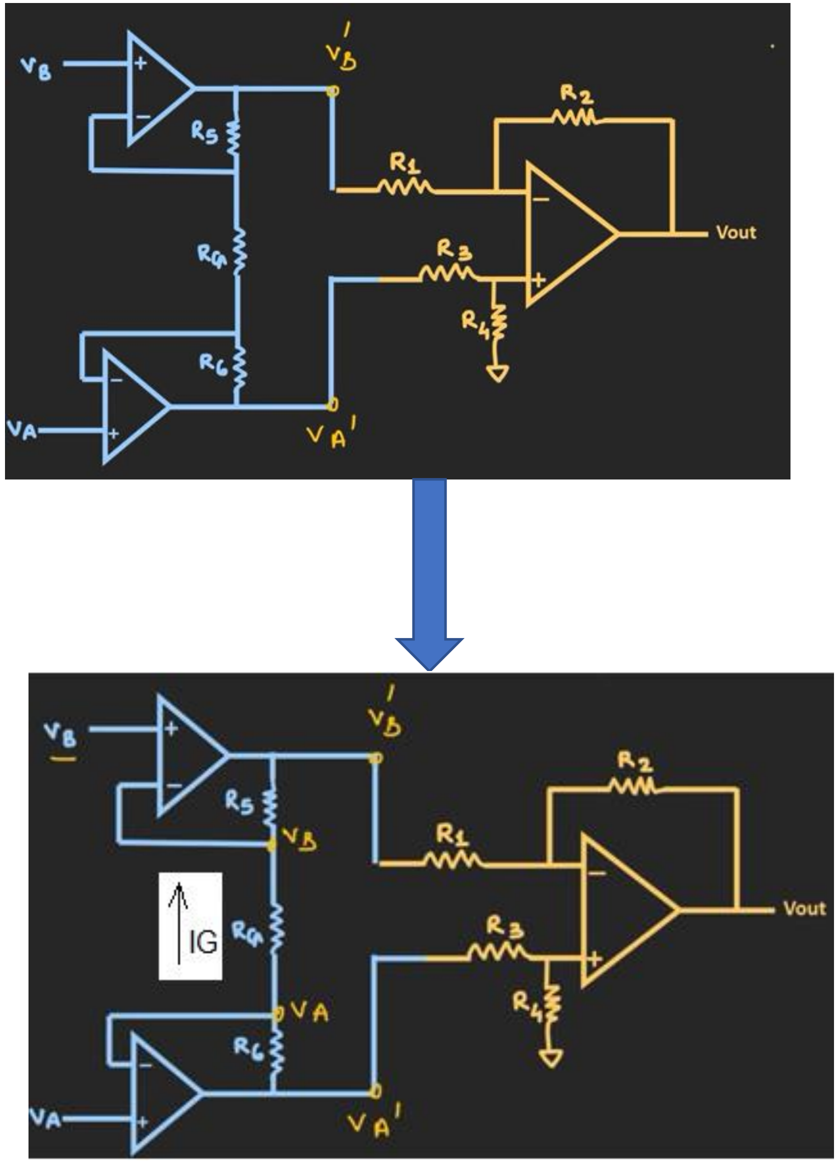
$$I_G = \frac{V_A - V_B}{R_G}$$

And:

$V'_A - V'_B = I_G(R_5 + R_G + R_6)$

If R5 = R6

$V'_A - V'_B = I_G(2R_5 + R_G)$

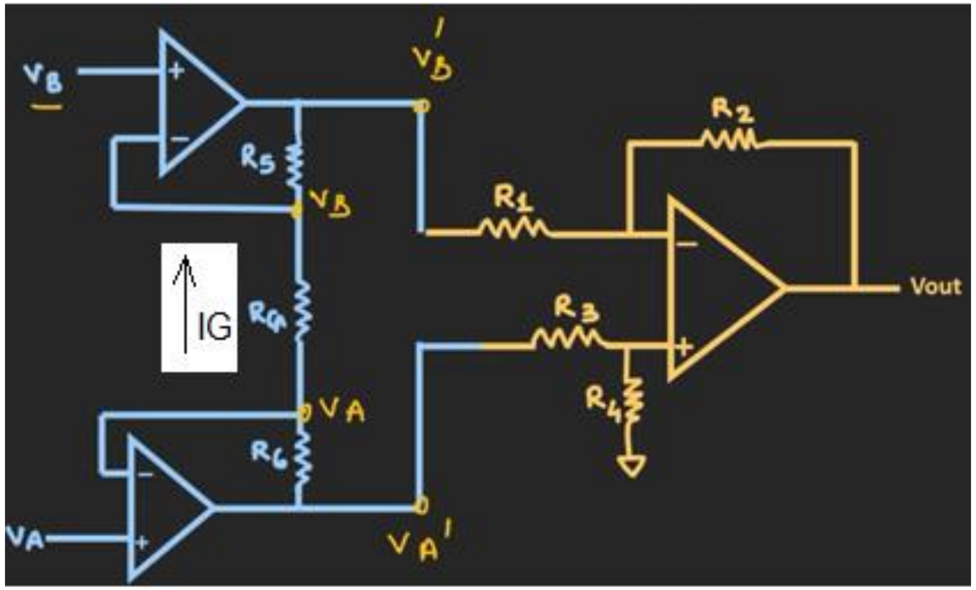


Instrumentational Amplifier

$$V_{out} = \frac{R_2}{R_1} \mathrm{I_G}(2\mathrm{R_5} + \mathrm{RG})$$

$$V_{out} = \frac{R_2}{R_1} \times \frac{V_A - V_B}{R_G} \times (2\mathrm{R_5} + \mathrm{RG})$$

$$V_{out} = \frac{R_2}{R_1} \times \left(1 + \frac{2R_5}{R_G}\right) \times (V_A - V_B)$$



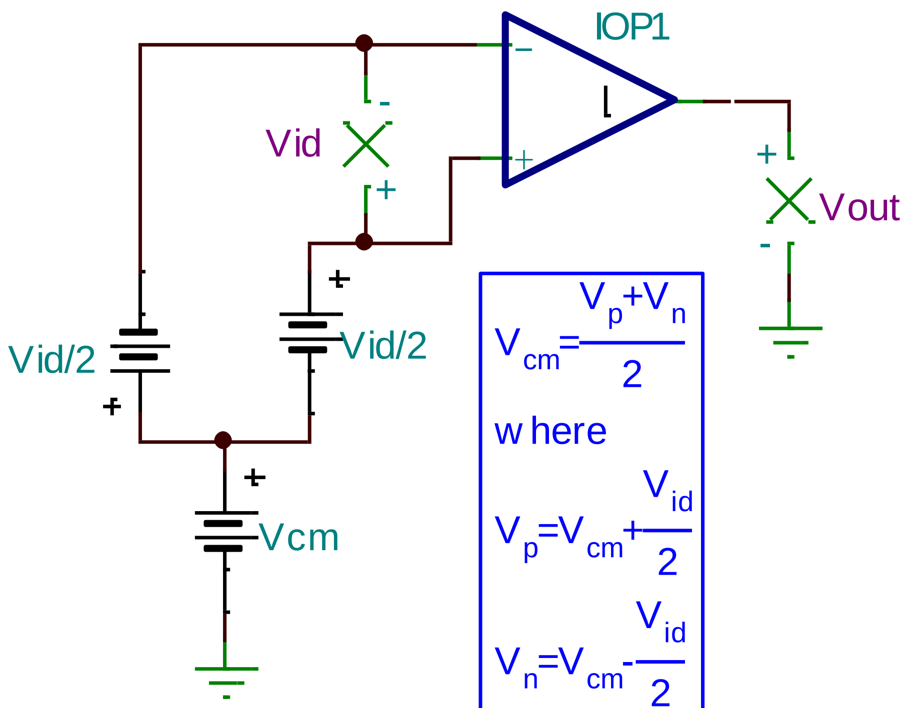
Common-mode rejection ratio (CMRR)

Data sheet

PARAMETER	TEST CONDITIONS		MIN	TYP	MAX	UNIT
Input offset voltage	$R_S \le 10\ k\Omega$	$T_A = 25°C$		1	5	mV
		$T_{AMIN} \le T_A \le T_{AMAX}$			6	mV
Input offset voltage adjustment range	$T_A = 25°C$, $V_S = \pm 20\ V$			±15		mV
Input offset current	$T_A = 25°C$			20	200	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			85	500	
Input bias current	$T_A = 25°C$			80	500	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$				1.5	μA
Input resistance	$T_A = 25°C$, $V_S = \pm 20\ V$		0.3	2		MΩ
Input voltage range	$T_{AMIN} \le T_A \le T_{AMAX}$		±12	±13		V
Large signal voltage gain	$V_S = \pm 15\ V$, $V_O = \pm 10\ V$, $R_L \ge 2\ k\Omega$	$T_A = 25°C$	50	200		V/mV
		$T_{AMIN} \le T_A \le T_{AMAX}$	25			
Output voltage swing	$V_S = \pm 15\ V$	$R_L \ge 10\ k\Omega$	±12	±14		V
		$R_L \ge 2\ k\Omega$	±10	±13		
Output short circuit current	$T_A = 25°C$			25		mA
Common-mode rejection ratio	$R_S \le 10\ \Omega$, $V_{CM} = \pm 12\ V$, $T_{AMIN} \le T_A \le T_{AMAX}$		80	95		dB

Common-Mode Voltage

- For a differential amplifier, common-mode voltage is defined as the average of the two input voltages.



$$V_{cm} = \frac{V_p + V_n}{2}$$

where

$$V_p = V_{cm} + \frac{V_{id}}{2}$$

$$V_n = V_{cm} - \frac{V_{id}}{2}$$

$$V_{out} = A_{dm}(V_{id}) + A_{cm}(V_{cm})$$

where

A_{dm} = Differential - mode gain

A_{cm} = Common - mode gain

CMRR and CMR

Common-Mode Rejection Ratio is defined as the ratio of the differential gain to the common-mode gain

$$CMRR = \frac{A_{dm}}{A_{cm}}$$

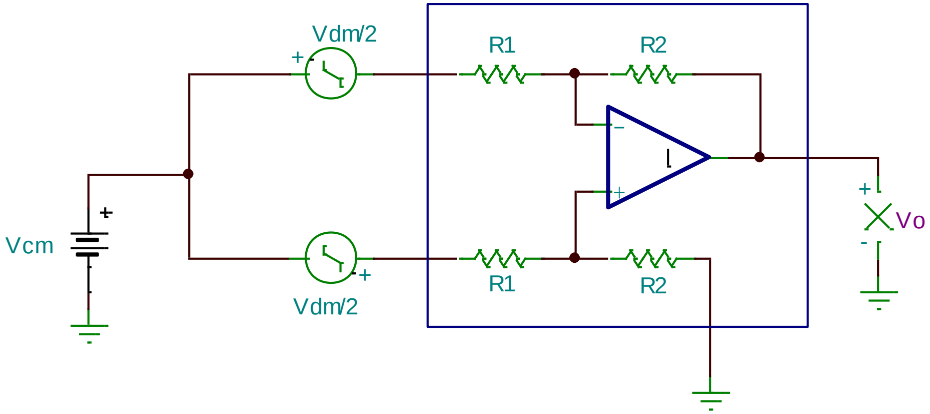
CMR is defined as follows:

$$CMR(dB) = 20\log_{10}(CMRR)$$

CMR and CMRR are often used interchangeably

CMRR of Differential Amplifiers

Let's replace V1 and V2 with our alternate definition of the inputs (in terms of differential-mode and common-mode signals)



$$V_1 = V_{cm} - \frac{V_{dm}}{2}$$

$$V_2 = V_{cm} + \frac{V_{dm}}{2}$$

$$V_o = \frac{R_2}{R_1}(V_2 - V_1)$$

$$V_o = \frac{R_2}{R_1}\left(\left(V_{cm} + \frac{V_{dm}}{2}\right) - \left(V_{cm} - \frac{V_{dm}}{2}\right)\right)$$

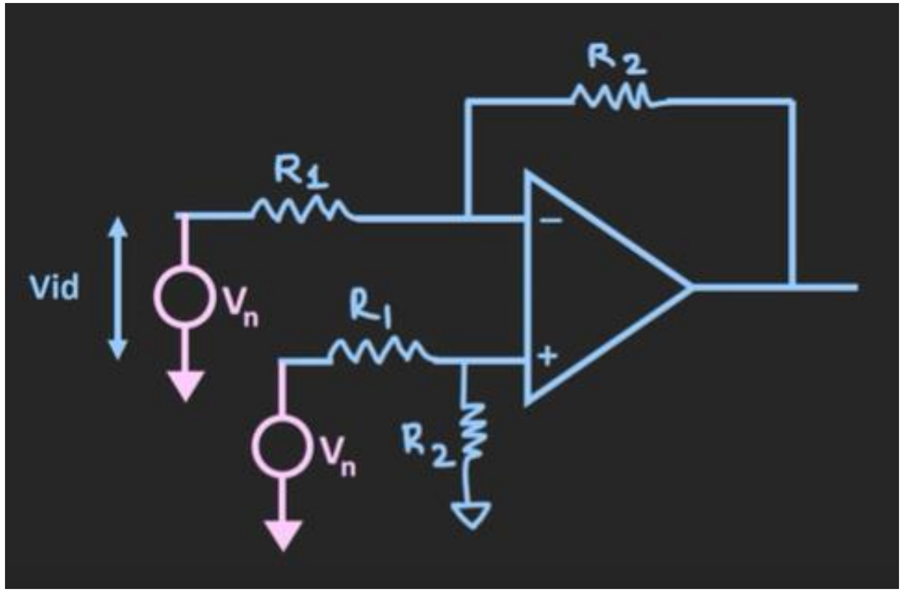
$$V_o = \frac{R_2}{R_1}(V_{dm})$$

It is readily observed that an ideal differential amplifier's output *should* only amplify the differential-mode signal…not the common-mode signal.

CMRR of Differential Amplifier

Example 6

The following differential amplifier has the following input data, discuss how well the amplifier will be able to suppress the common voltage



Output voltage due to differential input:

$$V_{out} = \frac{R2}{R1} \times (V2 - V1) = 50mV$$

R1= 1KΩ
R2=10 KΩ
CMRR= 90 dB
Vid= 5mV at 1 KHz
Vn= 2mV at 50Hz

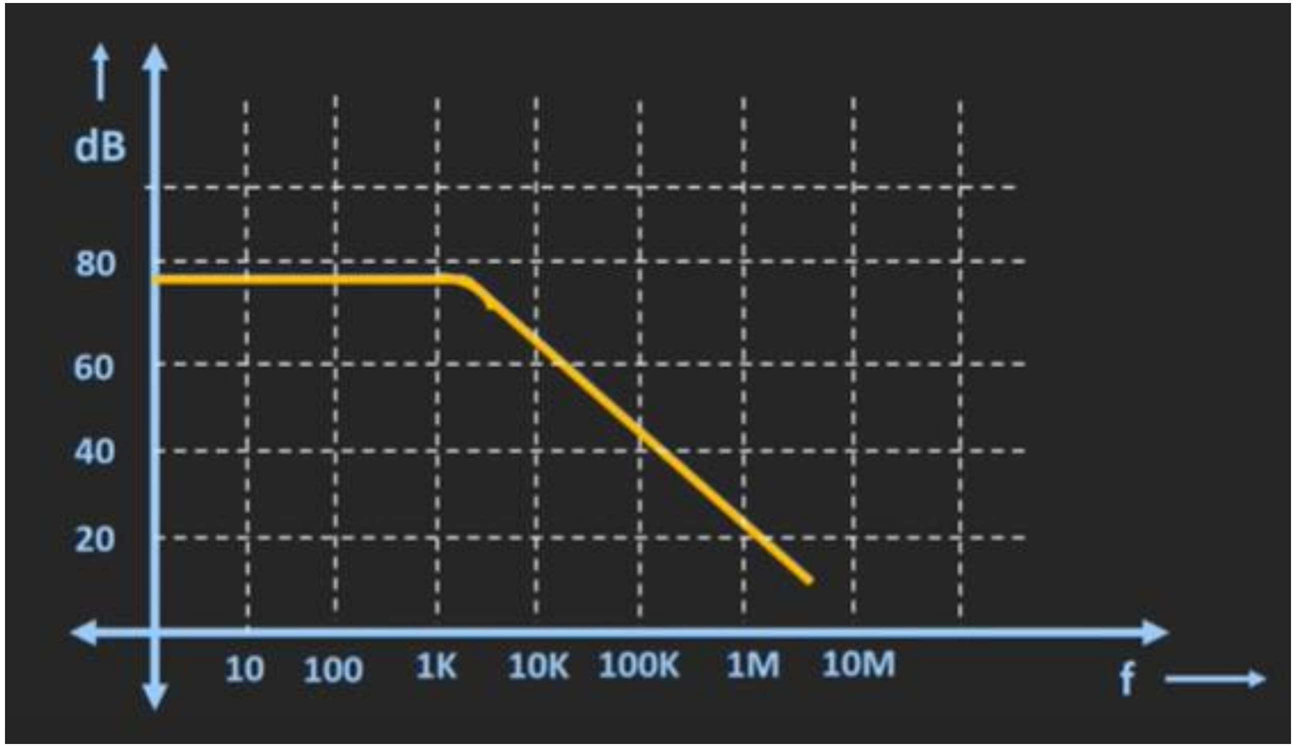
The CMRR = 90dB (which can be used for the closed loop configuration)

$$CMRR = 20log\left(\frac{A_d}{A_{CM}}\right) = 90 \Rightarrow CMRR = 20log\left(\frac{10}{A_{CM}}\right) = 90$$

$\Rightarrow$ $A_{CM} = 10/31623$

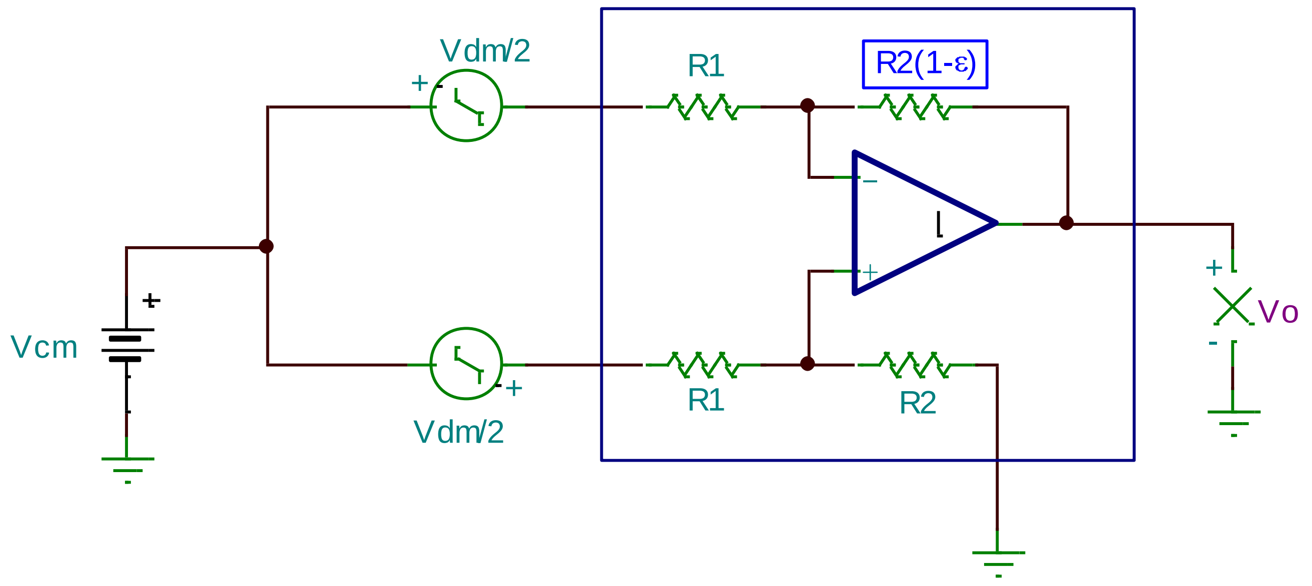
Output voltage due to common input: $$V_{out} = \frac{10}{31623} \times (2mV) = 0.63\mu V$$

CMRR of Differential Amplifier



CMRR of Differential Amplifiers

- This assumes that the operational amplifier is ideal and that the resistors are balanced.
- Keeping the assumption that the operational amplifier is ideal, let's see what happens when an imbalance factor (ε) is introduced.



CMRR of Differential Amplifiers

Using superposition we find that

$$V_o = \left(V_{cm} - \frac{V_{dm}}{2}\right)\left(-\frac{R_2(1-\varepsilon)}{R_1}\right) + \left(V_{cm} + \frac{V_{dm}}{2}\right)\left(\frac{R_2}{R_1+R_2}\right)\left(1+\frac{R_2(1-\varepsilon)}{R_1+R_2(1-\varepsilon)}\right)$$

After some algebra we find that:

$$V_o = A_{dm}V_{dm} + A_{cm}V_{cm}$$

where

$$A_{dm} = \frac{R_2}{R_1}\left(1-\frac{R_1+2R_2}{R_1+R_2}\times\frac{\varepsilon}{2}\right)$$

$$A_{cm} = \frac{R_2}{R_1+R_2}\times\varepsilon$$

As expected, an imbalance affects the differential and common-mode gains, which will affect CMRR!
As the error->0, Adm->R2/R1 and Acm->0.

CMRR of Differential Amplifiers

- Since we have equations for Acm and Adm, let's look at CMR

$$CMR(dB) = 20\log_{10}\left(\frac{A_{dm}}{A_{cm}}\right) = 20\log_{10}\left(\frac{\dfrac{R_2}{R_1}\left(1-\dfrac{R_1+2R_2}{R_1+R_2}\times\dfrac{\varepsilon}{2}\right)}{\dfrac{R_2}{R_1+R_2}\times\varepsilon}\right)$$

- If the imbalance is sufficiently small we can neglect its effect on Adm
- With that and some algebra we find:

$$CMR(dB) \cong 20\log_{10}\left(\frac{1+\dfrac{R_2}{R_1}}{\varepsilon}\right)$$

CMRR of Differential Amplifiers

- This equation shows two very important relationships

$$CMR(dB) \cong 20\log_{10}\left(\frac{1+\frac{R_2}{R_1}}{\varepsilon}\right)$$

  - As the gain of a difference amplifier increases (R2/R1), CMR increases
  - As the mismatch (ε) increases, CMR decreases

- Please remember that this just shows the effects of the resistor network and assumes an ideal amplifier