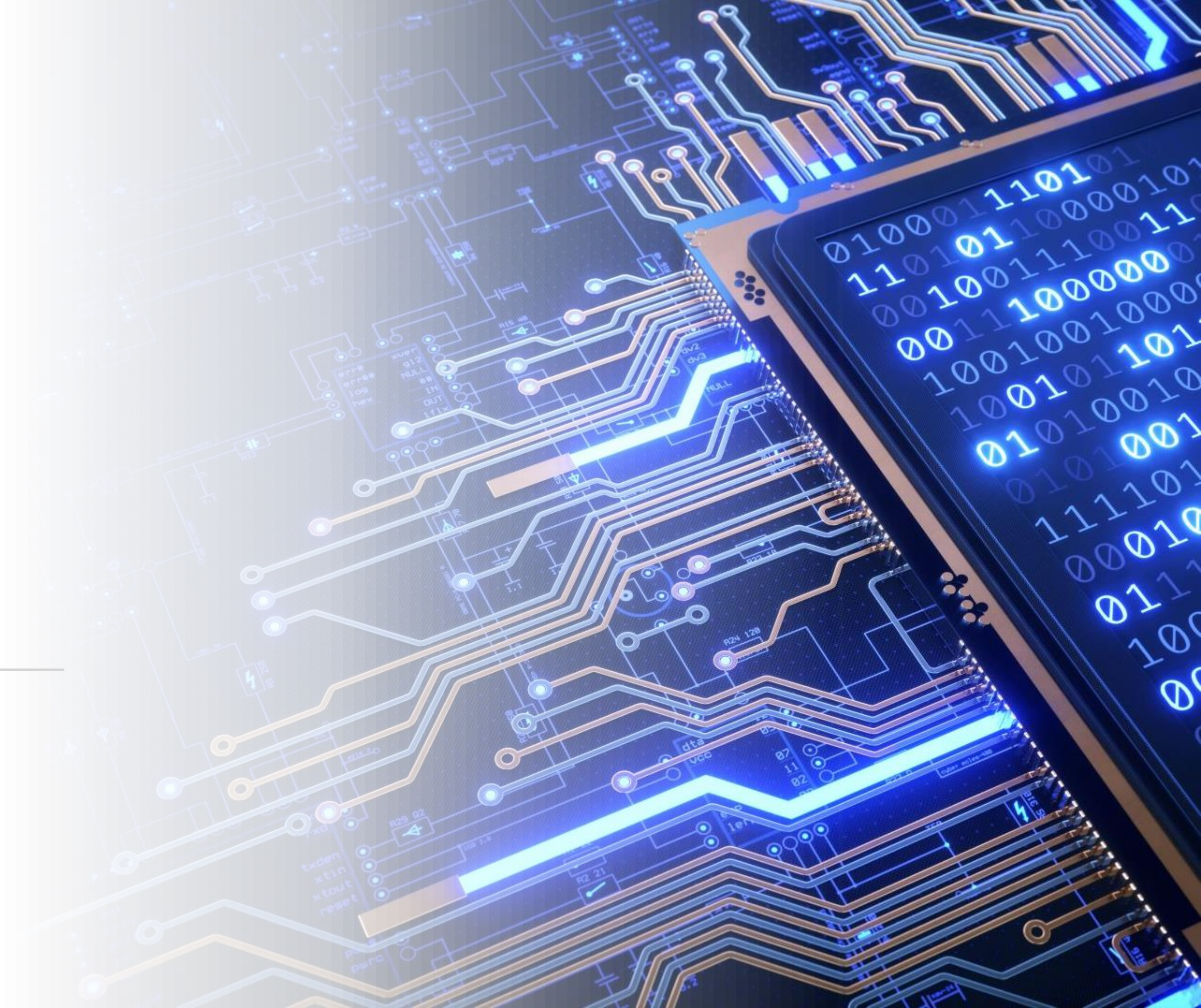
Operational Amplifier (OP-AMP)



Operational Amplifier

An **Operational Amplifier** (often **op-amp** or **opamp**) is a DC coupled high-gain electronic voltage amplifier with a differential input and usually, a single-ended output.

Multiple stages connected in cascade

- Op-amp is basically a multistage amplifier which uses several amplifier stages interconnected to each other in a complicated manner.
- The amplifier can be configured to perform a variety of operations such as amplification, addition, subtraction, differentiation and integration. Hence the name is operational amplifier (OP-AMP).

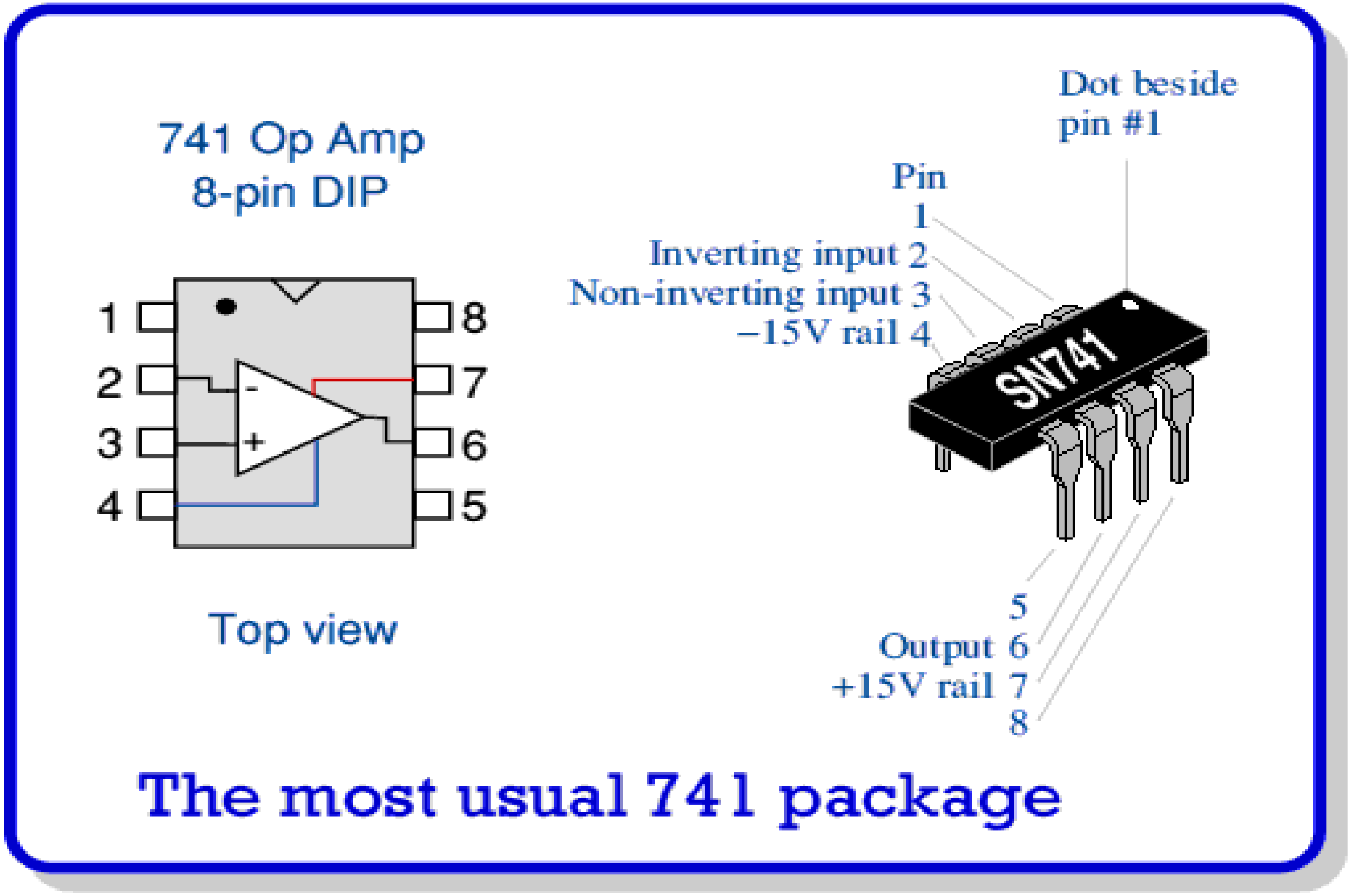
IC 741 → 8 pin IC

- The integrated Op-amp offers all the advantages of monolithic integrated circuits such as small size, high reliability, reduced cost, less power consumption.

distortion in o/p is less

- IC 741 is extremely popular and is used in a variety of applications.

Pin Configuration of OP-AMP IC 741



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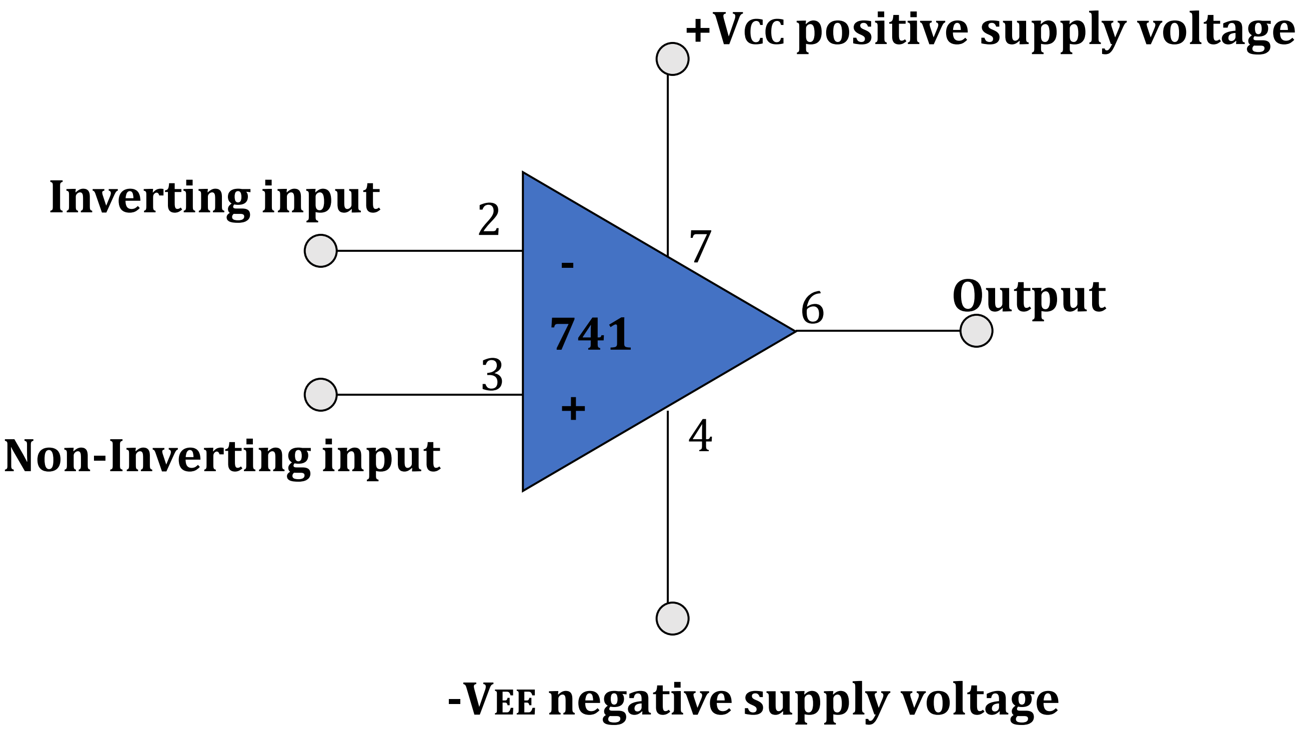
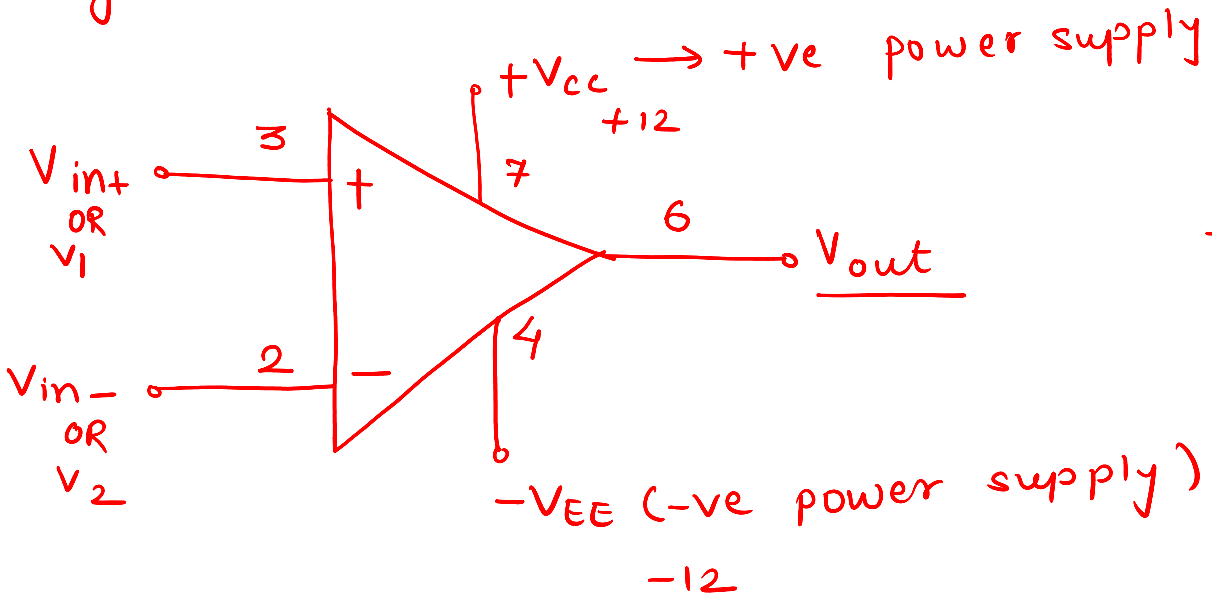
Symbol and Terminal



The **Operational Amplifier** (**op amp**) was **invented** in the 40's. Bell Labs filed a patent in 1941 and many consider the first practical **op amp** to be the vacuum tube K2-W **invented** in 1952 by George Philbrick.

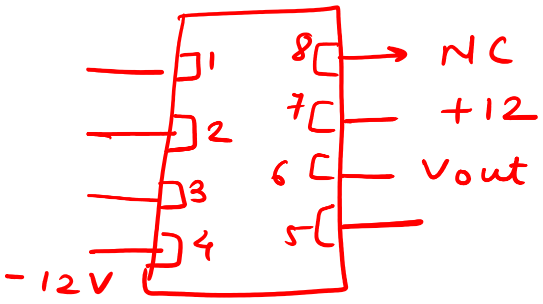
Symbol:



→ $V_{out} = A\,(V_{in+} - V_{in-})$

$= A\,(V_1 - V_2)$

5 V   3V

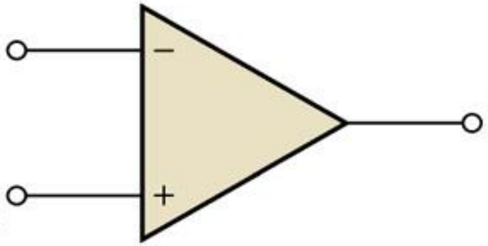


V_{in+} : Non-inverting i/p

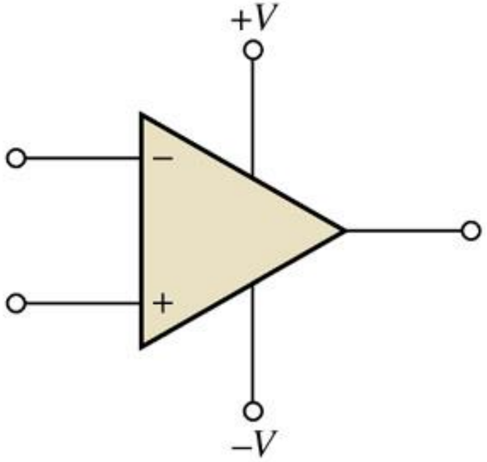
V_{in-} : Inverting i/p

Pin 1 and 5 : offset null.

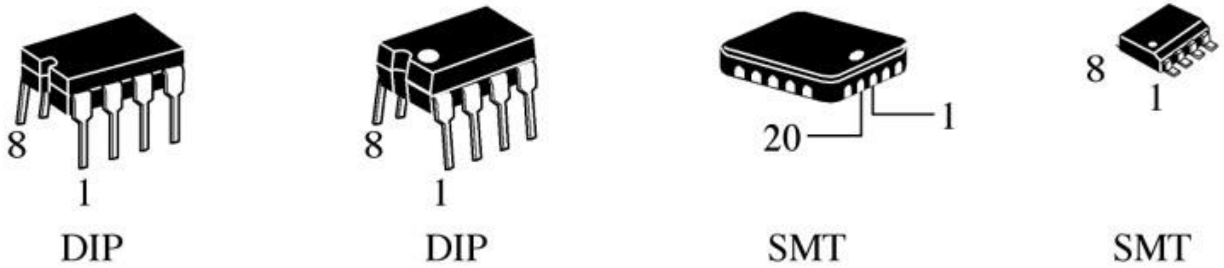
Op-amp Symbols and Packages.



(a) Symbol



(b) Symbol with dc supply connections



(c) Typical packages. Pin 1 is indicated by a notch or dot on dual-in-line (DIP) and surface-mount technology (SMT) packages, as shown.

Manufactures of OP-AMP IC 741

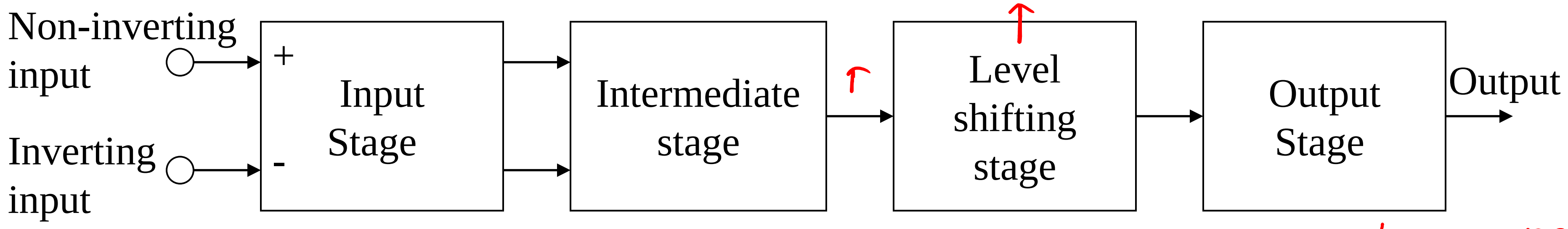
- The manufactures of Op-amp ICs are companies like Fairchild, National semiconductor, Motorola, Texas Instruments and Signetics.
- The identifying initials for some other companies are as follows:

1. National semiconductors : LM 741
2. Motorola : MC 741
3. RCA : CA 741
4. Texas instruments : SN 52741
5. Signetics : N 5741

Block Diagram of a Typical OP-AMP

To shift the dc level of o/p downward towards ground

dc level o/p



provide low o/p impedance

Dual input
Balanced
Output
Differential
amplifier

Dual input
unbalanced → single
Output
Differential
amplifier

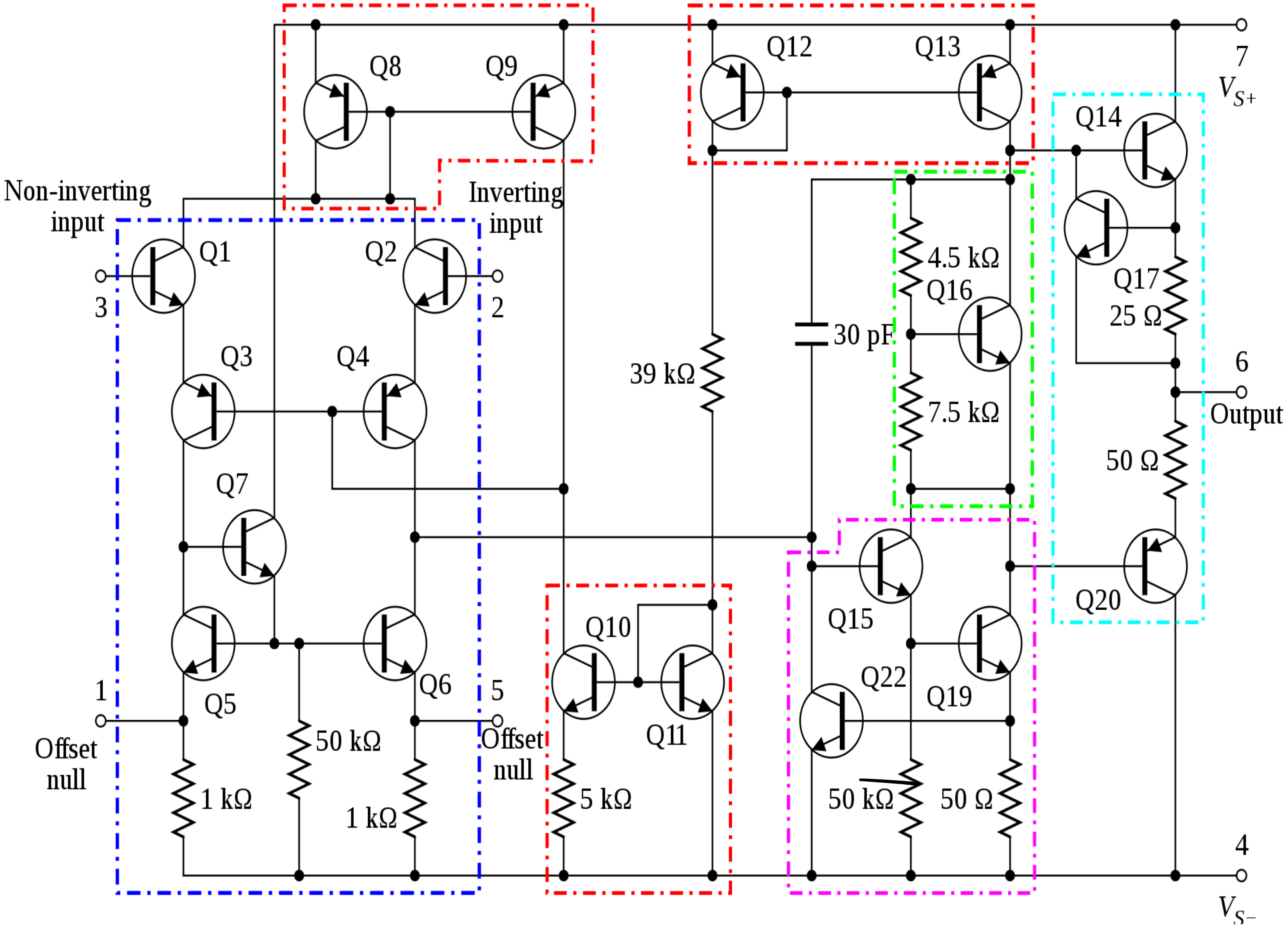
single ended.

Emitter follower
Using constant
Current source

common collector

providing constant current

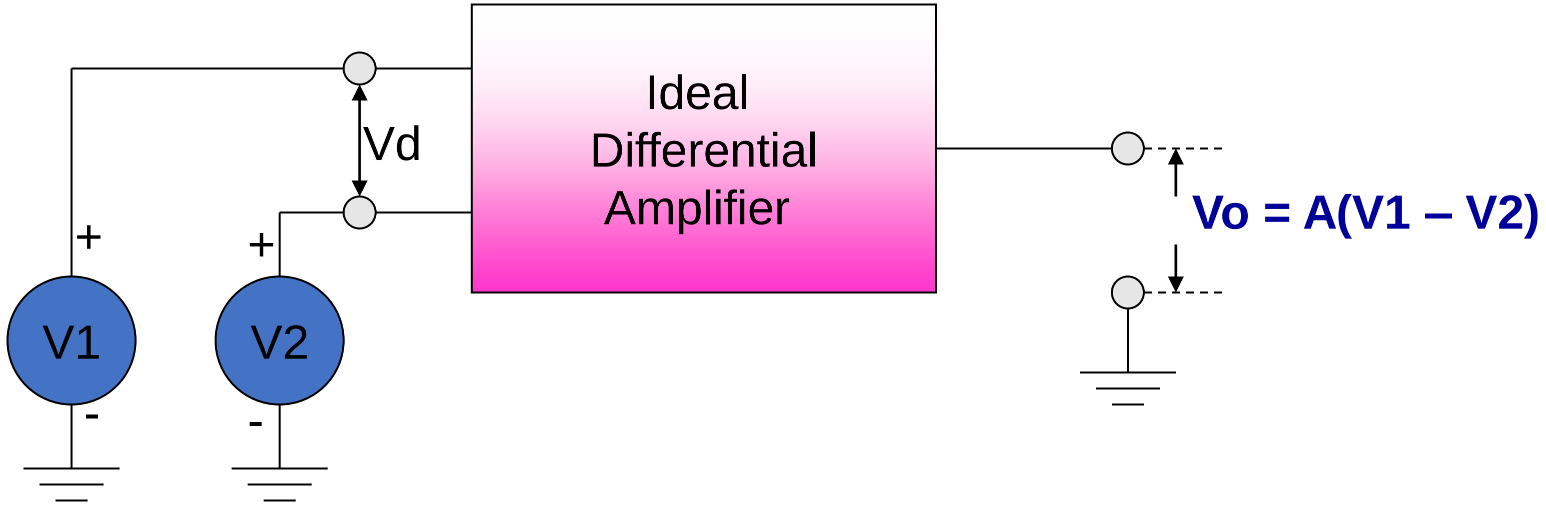
Complementary
Symmetry
Push-pull
amplifier

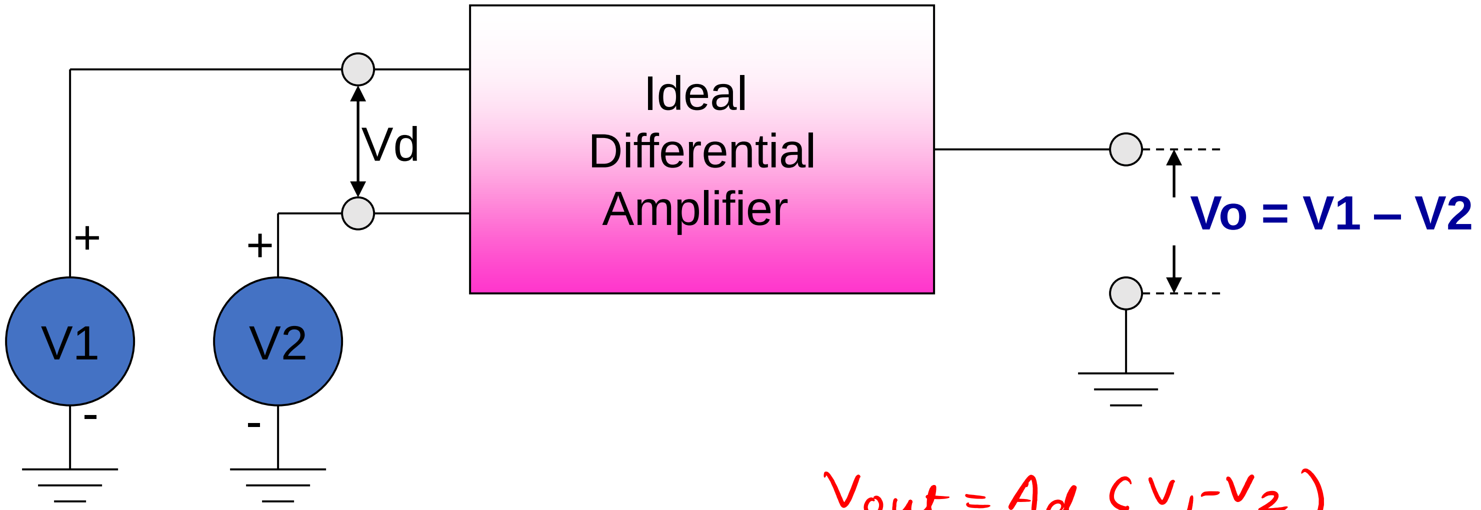


Non-inverting input
3
Q1
Q2
Inverting input
2
Q8
Q9
Q12
Q13
7
V_{S+}
Q14
Q3
Q4
Q7
Q5
Q6
1
Offset null
5
Offset null
1 kΩ
50 kΩ
1 kΩ
Q10
Q11
5 kΩ
39 kΩ
30 pF
4.5 kΩ
Q16
7.5 kΩ
Q17
25 Ω
6
Output
50 Ω
Q15
Q20
Q22
Q19
50 kΩ
50 Ω
4
V_{S-}

Ideal Differential Amplifier

- An ideal differential amplifier is expected to amplify the differential signal present between its two inputs.
- It is also the basic stage of an integrated Op-amp with differential input.





$V_{out} = A_d (V_1 - V_2)$

Differential Gain -

- Vo = Ad (V1 – V2), where Ad is called as the differential gain.
- The differential gain can be defined as the gain with which the differential amplifier amplifies the differential signal.

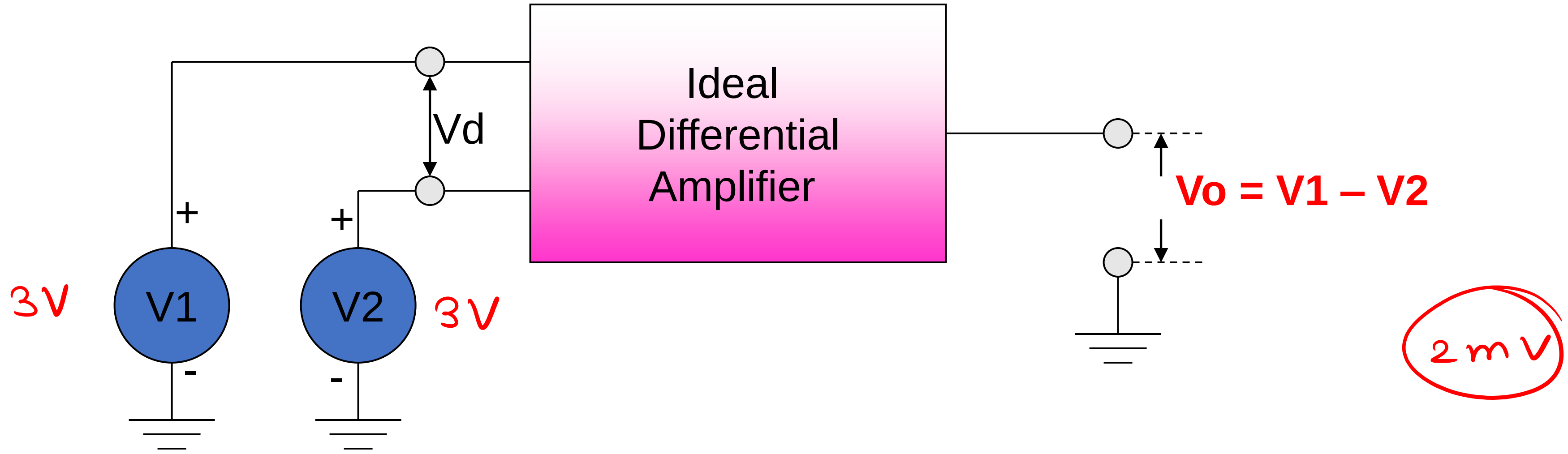
$$V_o = A_d V_d \qquad \text{as,} \quad V_d = V_1 - V_2$$

$$\text{Gain} \quad A_d = V_o / V_d$$

$$A_d\,(dB) = 10 \log_{10} [\, V_o / V_d \,]$$

$$A_d\,(dB) = 10 \log_{10} \left(\frac{V_o}{V_d}\right)$$

$$= 10 \log_{10} \left(\frac{V_o}{V_1 - V_2}\right)$$



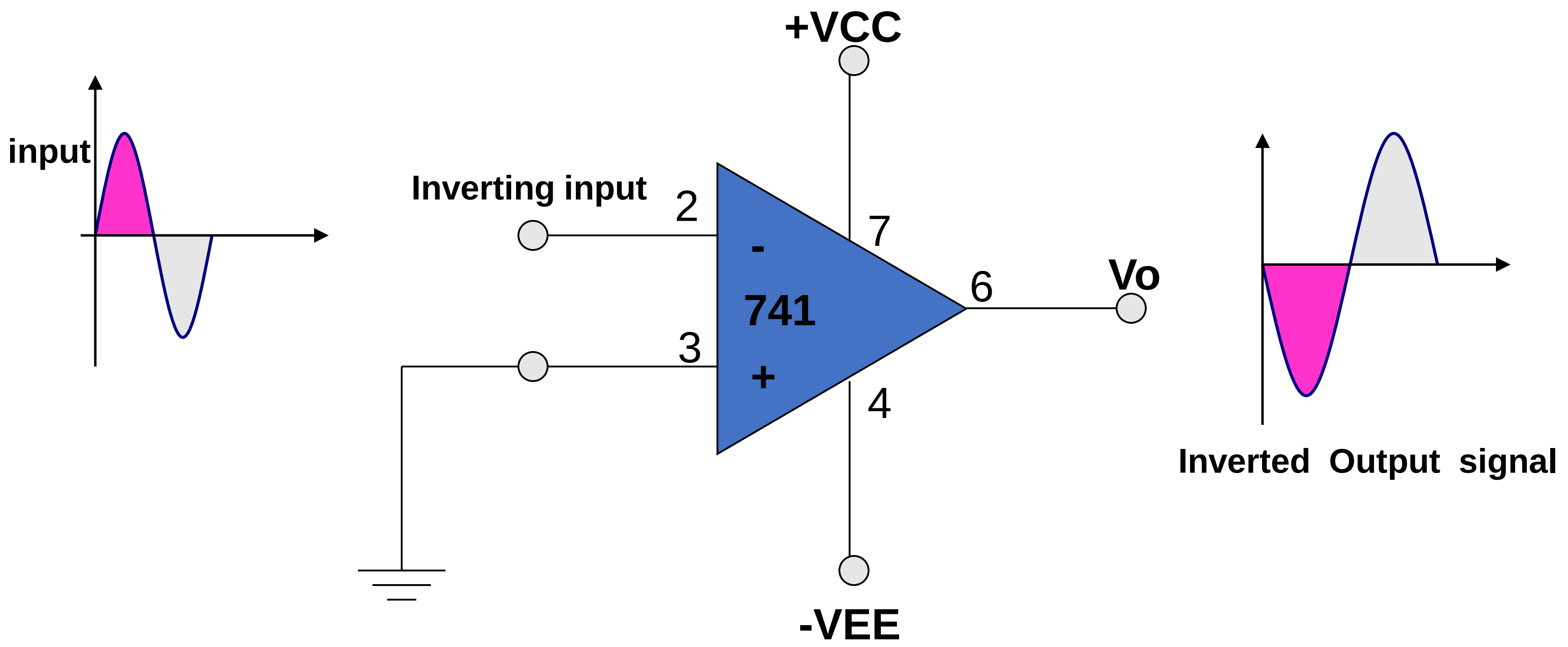
$V_{out} = A_d(V_1 - V_2)$
$= 0$

Common Mode Signal

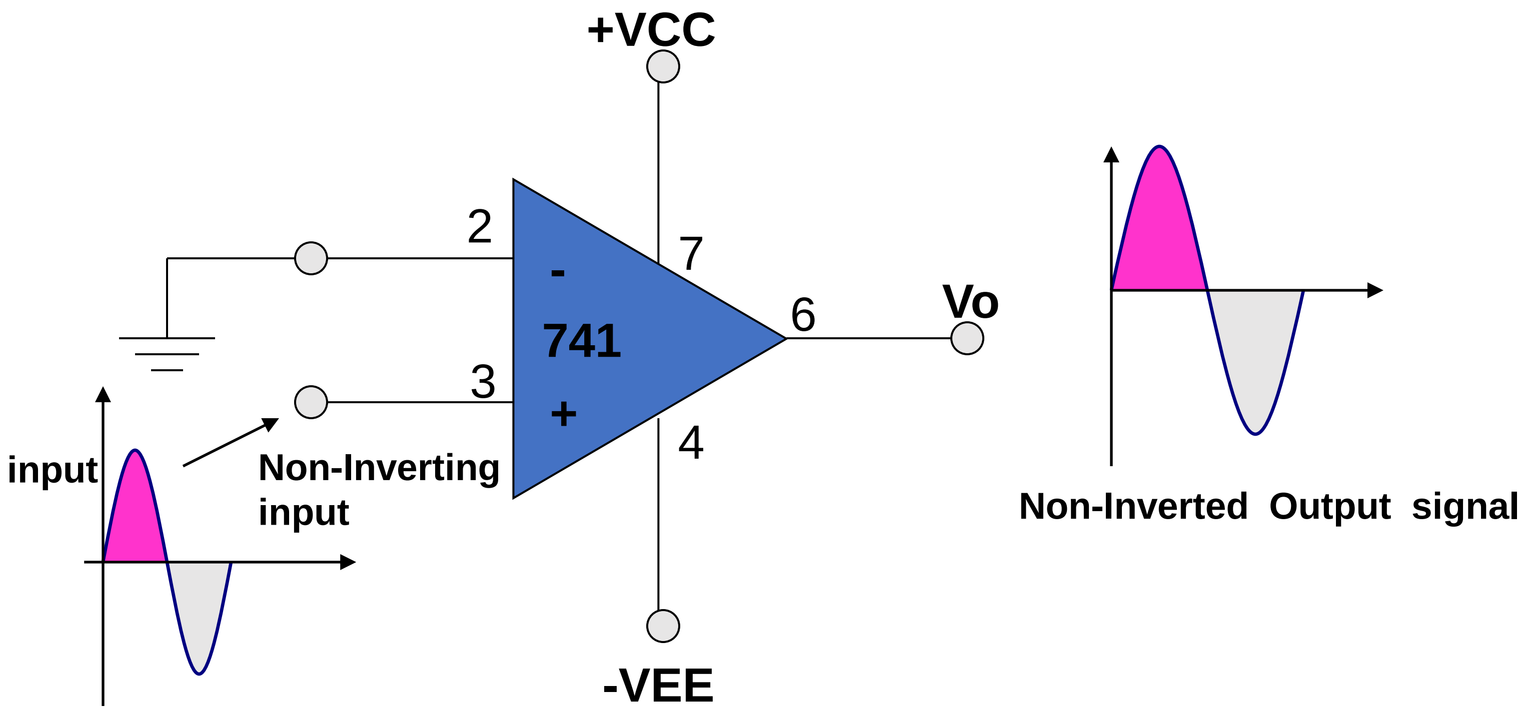
$(V_1 = V_2 = V)$

- A common signal to both the input terminals (i.e. V1=V2=V) is called as common mode signal.
- The output voltage produced by an ideal differential amplifier is zero for the common mode signal.

Input and output signals 180^0 phase shift when the input signal is applied to the inverting (-) terminal.



Input and output signals 0^0 phase shift when the input signal is applied to the Non-inverting (+) terminal.



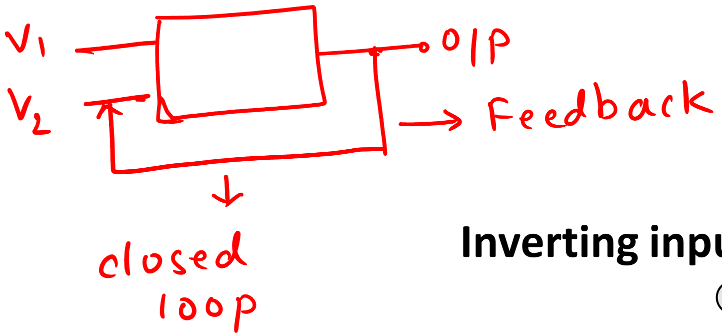
Equivalent Circuit of an OP-AMP

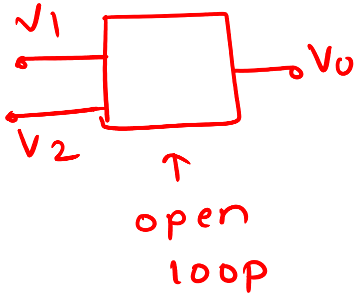
R_i = Input impedance (∞)

A_v = open loop gain of op-amp (∞)

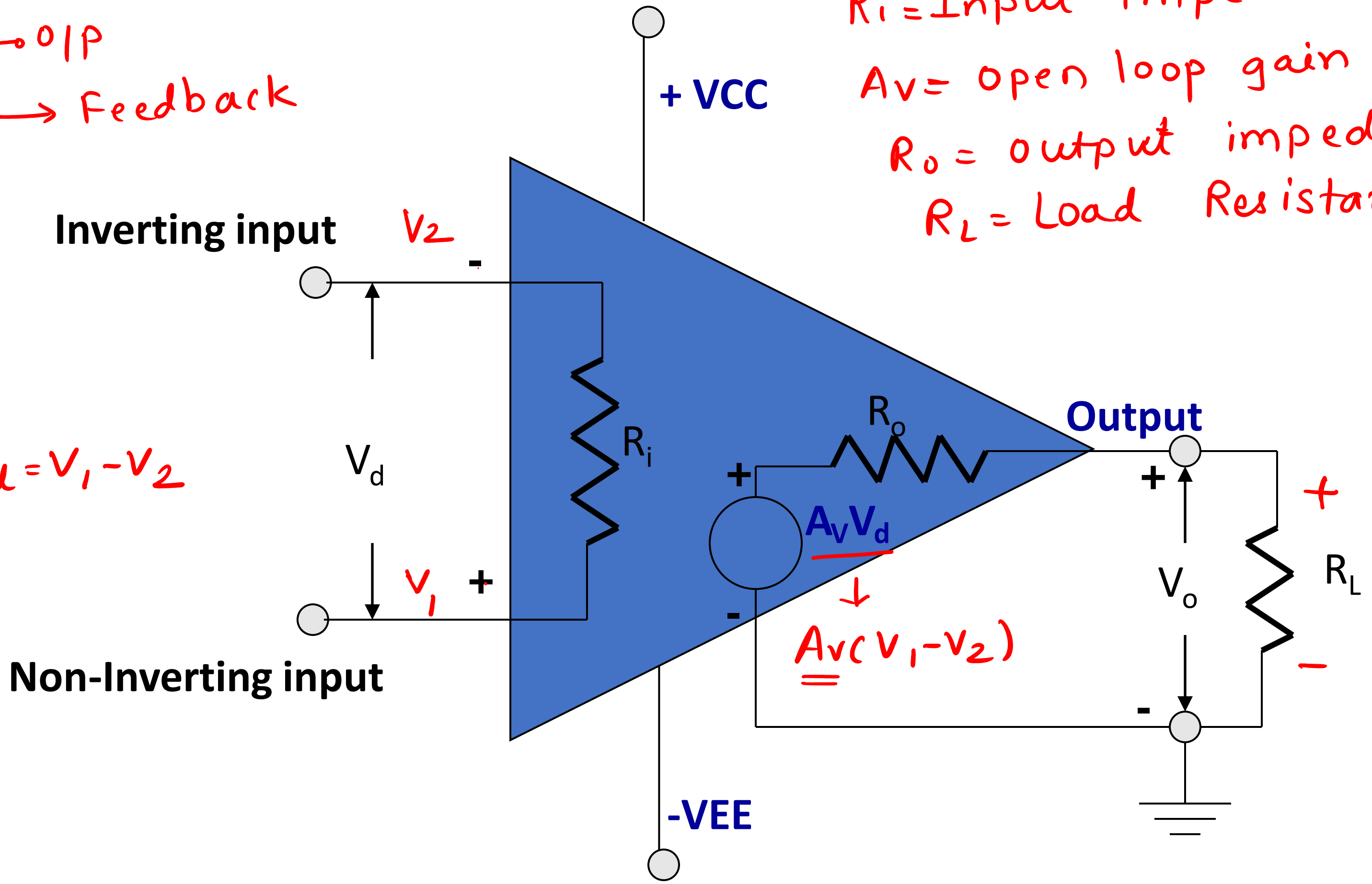
R_o = output impedance (0)

R_L = Load Resistance





$V_d = V_1 - V_2$



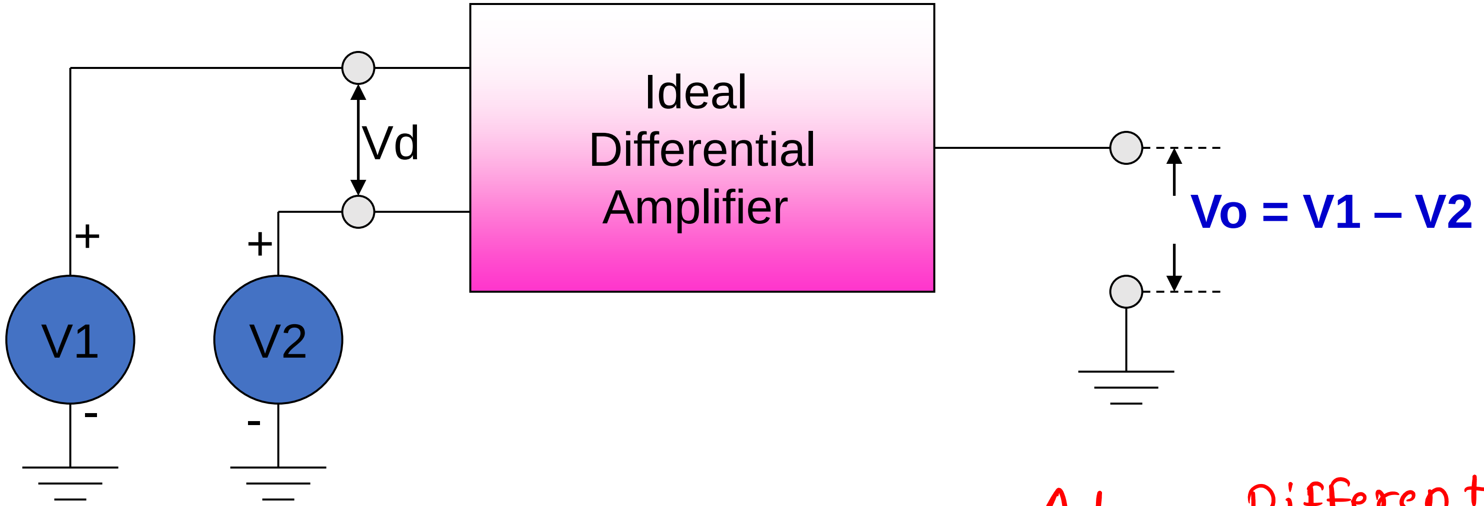
$A_d = 2 \times 10^3$

$A_c = 10$

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

$= 200$

$= 46 dB.$



Common Mode Rejection Ratio (CMRR)

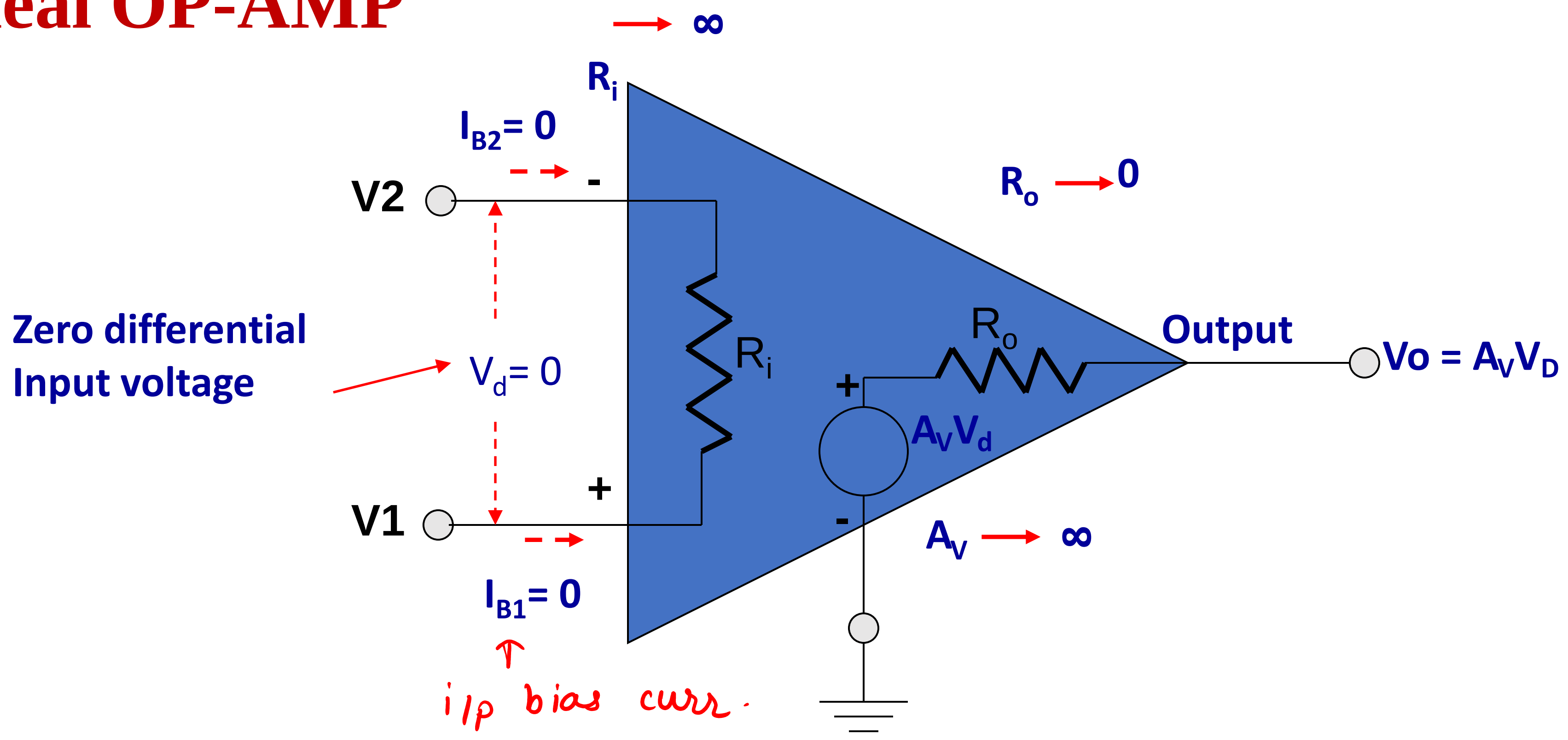
$CMRR = \frac{A_d}{A_c} = \frac{\text{Differential Gain}}{\text{Common mode Gain}} = \rho$

- Common mode rejection ration (CMRR) is the ability of a differential amplifier to reject the common mode signal successfully.
- CMRR is defined as the ratio of differential gain Ad and common mode gain Ac. It is denoted by letter "ρ".

$CMRR_{(dB)} = 20 \log_{10} \left(\frac{A_d}{A_c} \right)$

- CMRR = ρ = $|Ad / Ac|$
- Ideally CMRR should be infinite and practically it should be as high as possible.

The Ideal OP-AMP



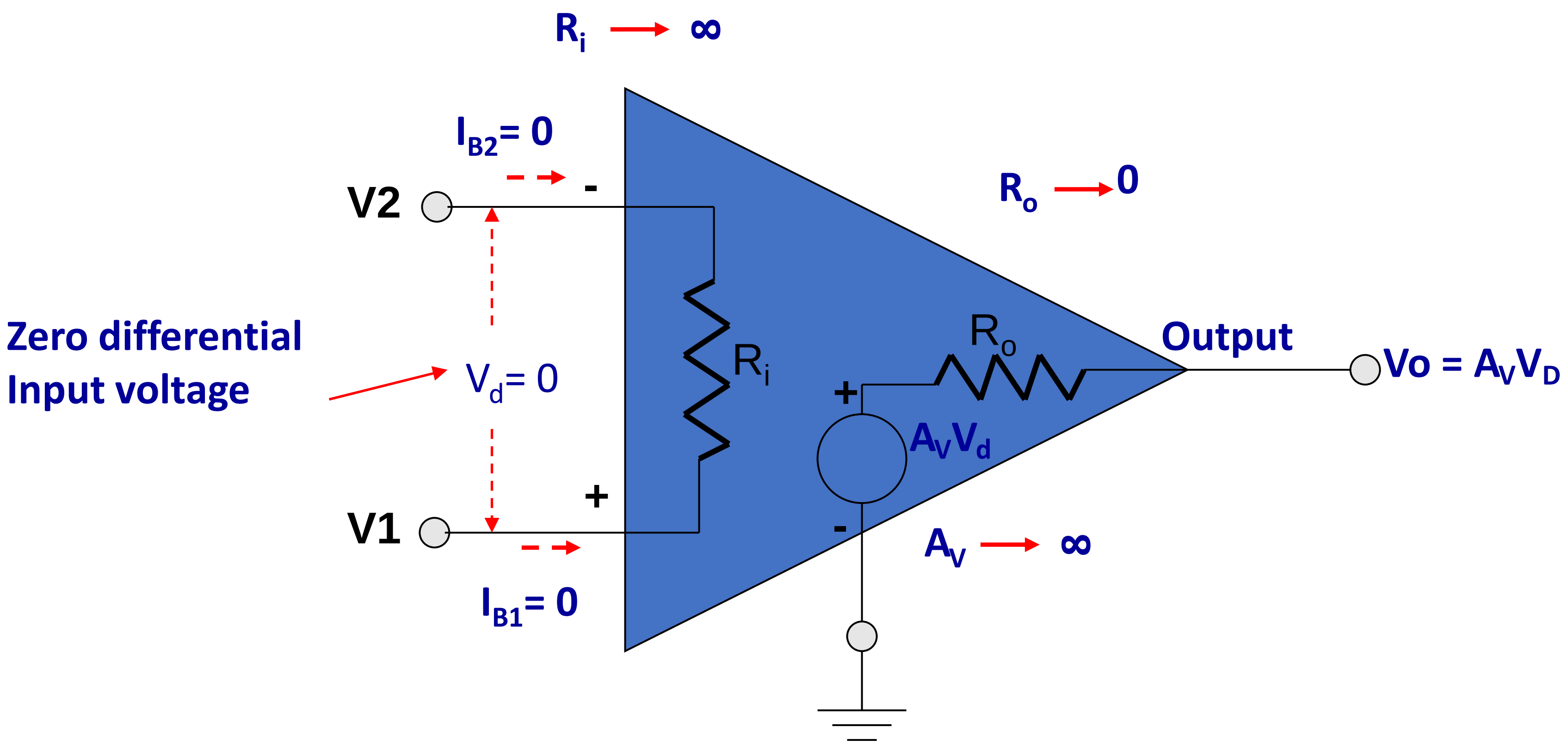
Important characteristics of Op-Amp

1. Infinite voltage gain ($A_V \to \infty$)   741 → 2×10^5

   The open loop gain of an ideal OP-AMP is denoted by Av. It is the differential voltage gain and its value for an ideal OP-AMP is infinite.

   $Vo = A_V V_D$

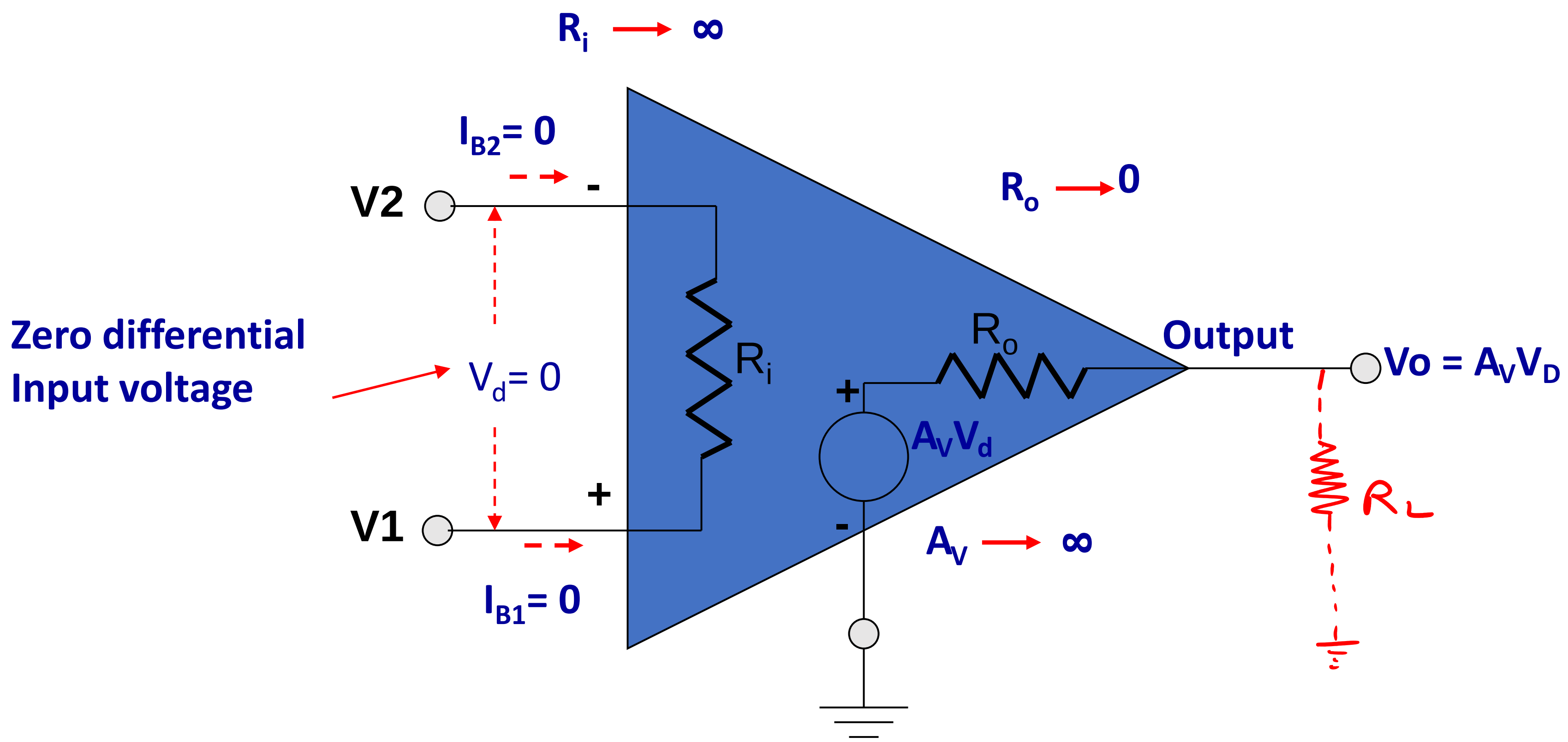
The Ideal OP-AMP



2. Infinite Input Resistance ($R_i \rightarrow \infty$)

- The input resistance Ri of an ideal OP-amp is infinite.
- Due to this, the current flowing in each input terminal will be zero. $I_{B1} = 0$ $I_{B2} = 0$
- Due to infinite input resistance, almost any source can drive it and there is no loading of the source.

The Ideal OP-AMP



3. Zero Output Resistance ($R_O = 0$)

- The output resistance Ro of an ideal OP-amp is zero.
- Due to this, the ideal Op-amp can handle infinite number of other devices.

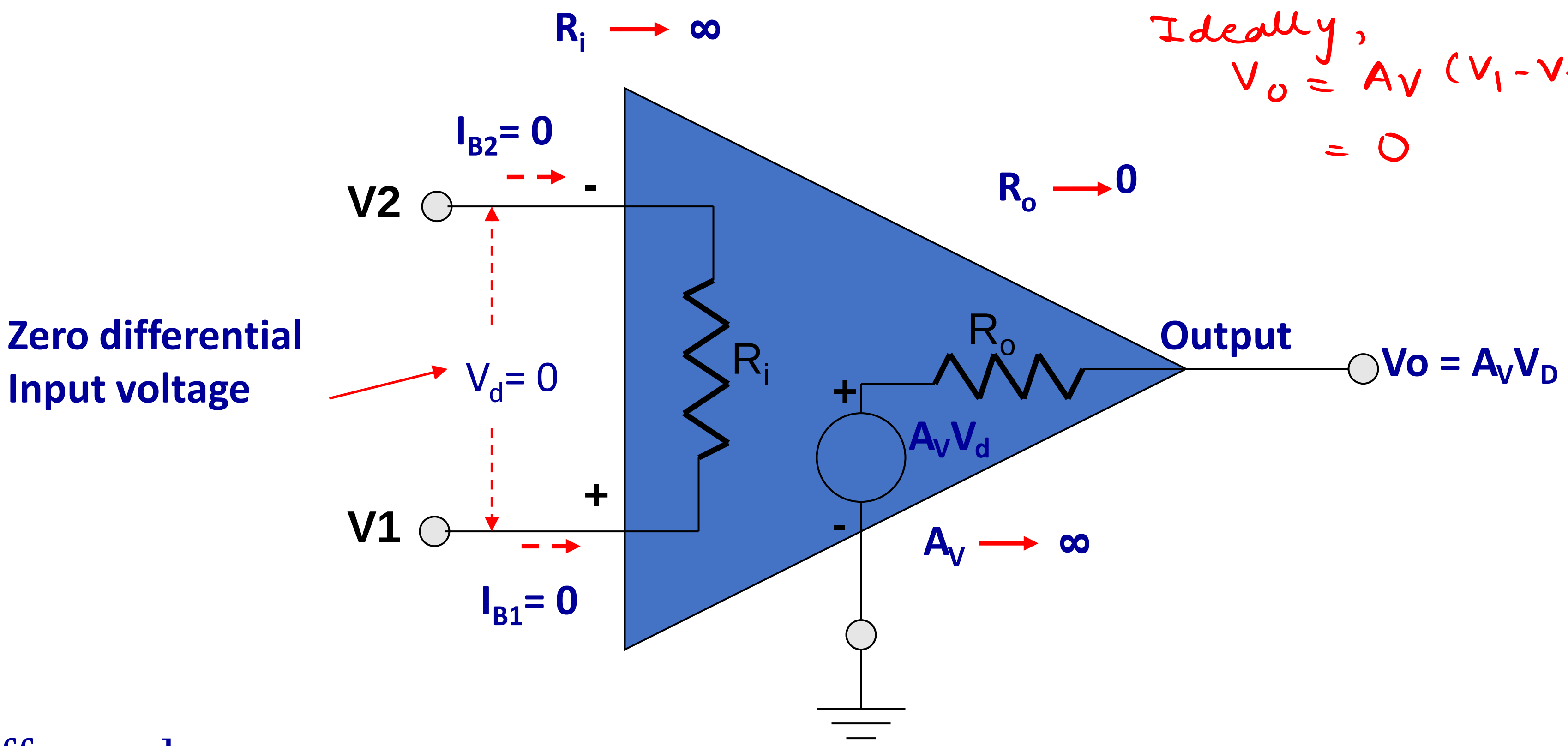
The Ideal OP-AMP

When $V_1 = V_2 = V$,

Ideally,

$V_o = A_V (V_1 - V_2)$

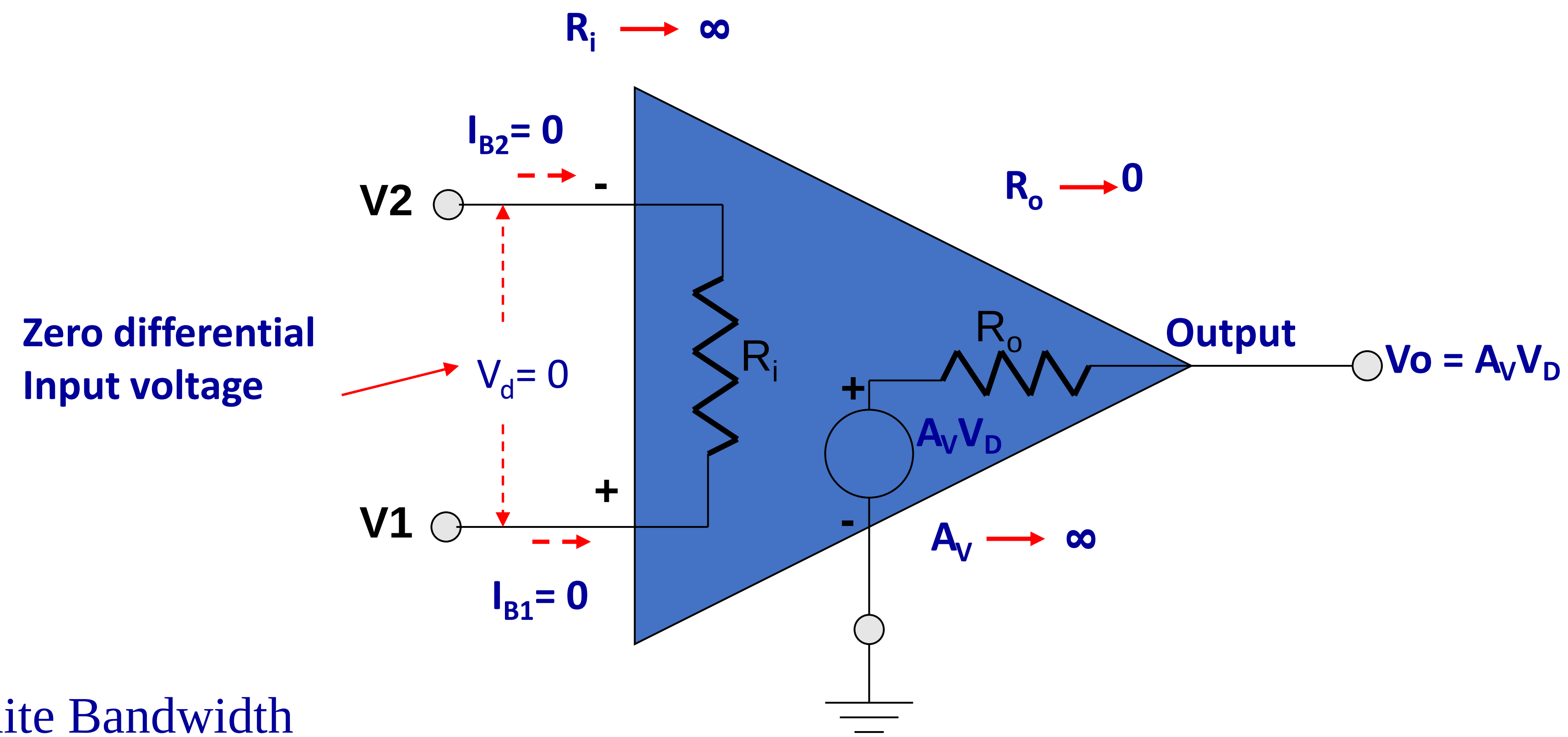
$= 0$



4. Zero offset voltage (μV / mV)

- In practical Op-amps a small output voltage is present even though both the inputs V1 ad V2 are having a zero value. ($V_1 = V_2 = 0$)
- This voltage is called as the offset voltage. For ideal Op-amp the offset voltage is zero.
- That means output voltage is zero when input voltage is zero.

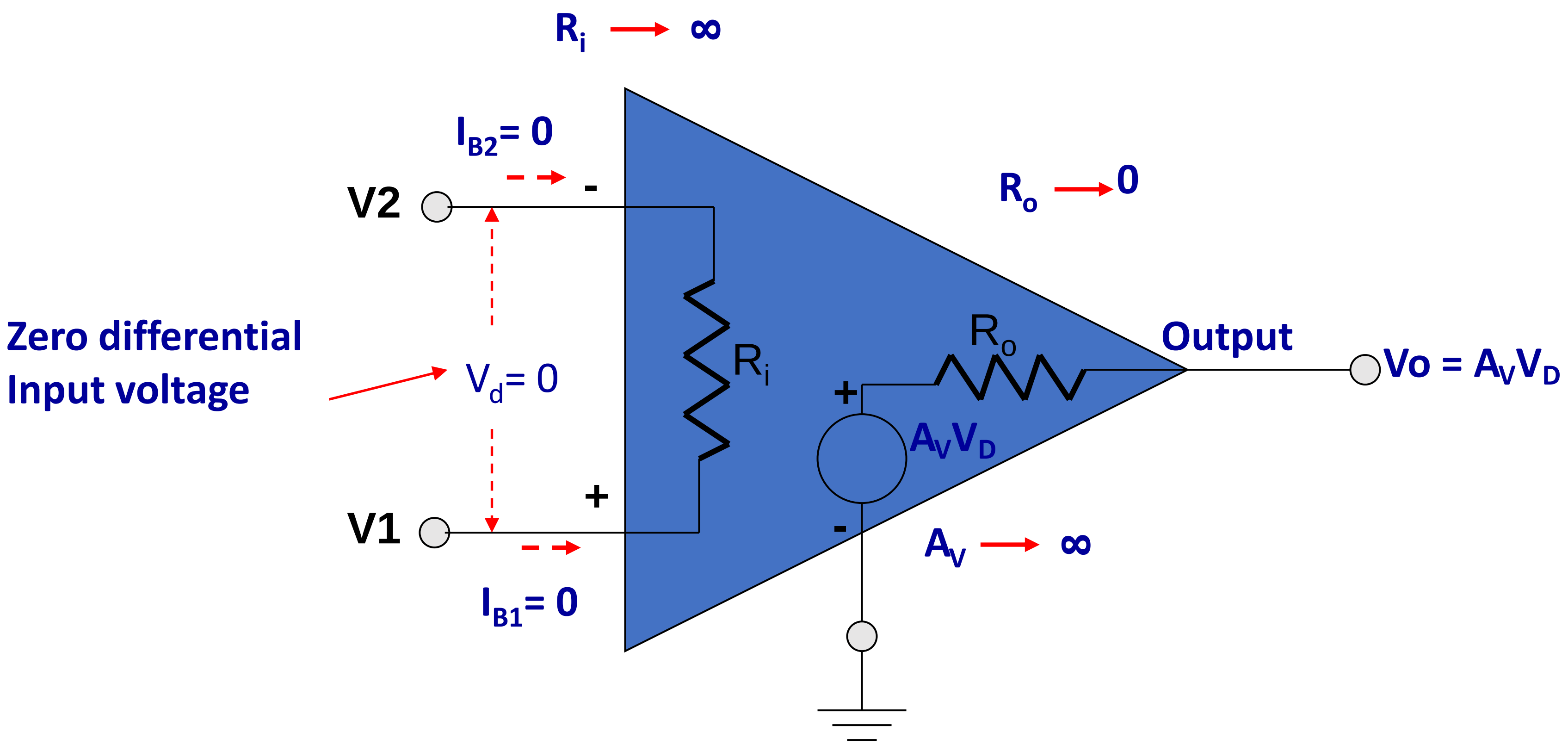
The Ideal OP-AMP



5. Infinite Bandwidth

- Bandwidth of an amplifier is the range of frequencies over which all the signal frequencies are amplified almost equally.
- The bandwidth of an ideal Op-amp is infinite. So, it can amplify any frequency from zero to infinite hertz.
- Thus, the gain of an ideal amplifier is constant from zero to infinite hertz.

The Ideal OP-AMP



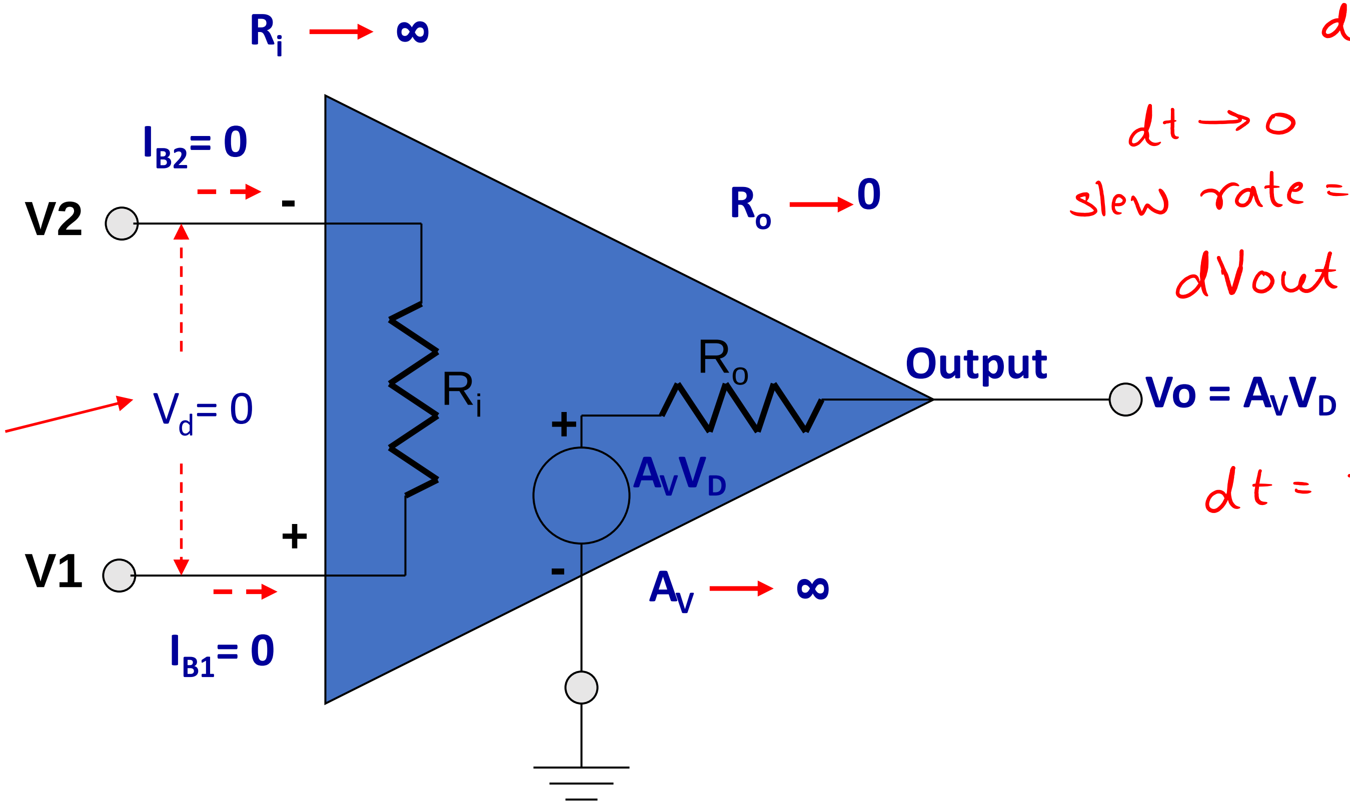
6. Infinite CMRR

- For an Op-amp, the common mode rejection ratio (CMRR) id defined as the ratio of differential gain to common mode gain.
- CMRR is infinite for the ideal Op-amp.

The Ideal OP-AMP

slew rate = $\frac{dV_{out}}{dt}$ $\left(\frac{V}{\mu sec}\right)$

$V_1 = 5V$
$V_2 = 3V$
$\rightarrow$
$V_1 = 7V$
$V_2 = 5V$

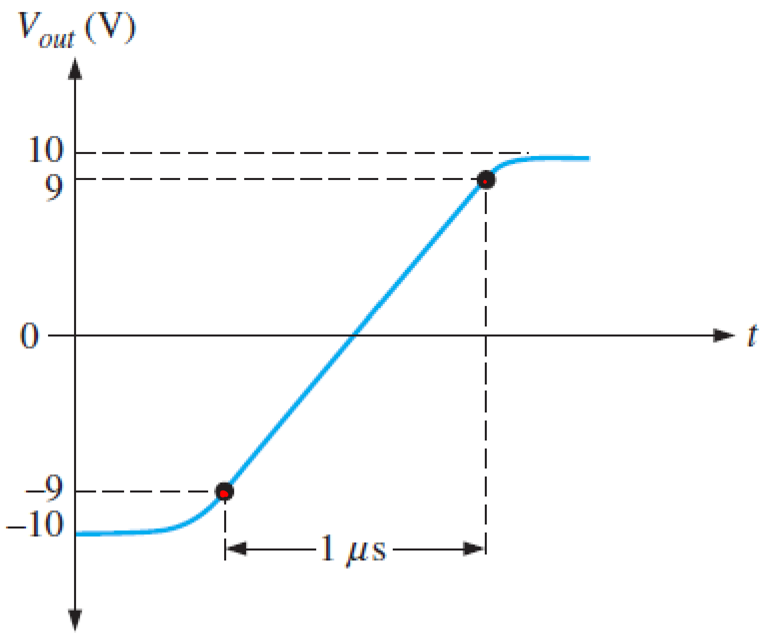


$dt \rightarrow 0$
slew rate $= \infty$.
dV_{out} = change in o/p vtg
dt = time required

7. Infinite Slew Rate

- The slew rate of an ideal Op-amp is infinite so that the output voltage changes occur simultaneously with the input voltage changes.

The output voltage of a certain op-amp appears as shown in Figure in response to a step input. Determine the slew rate.



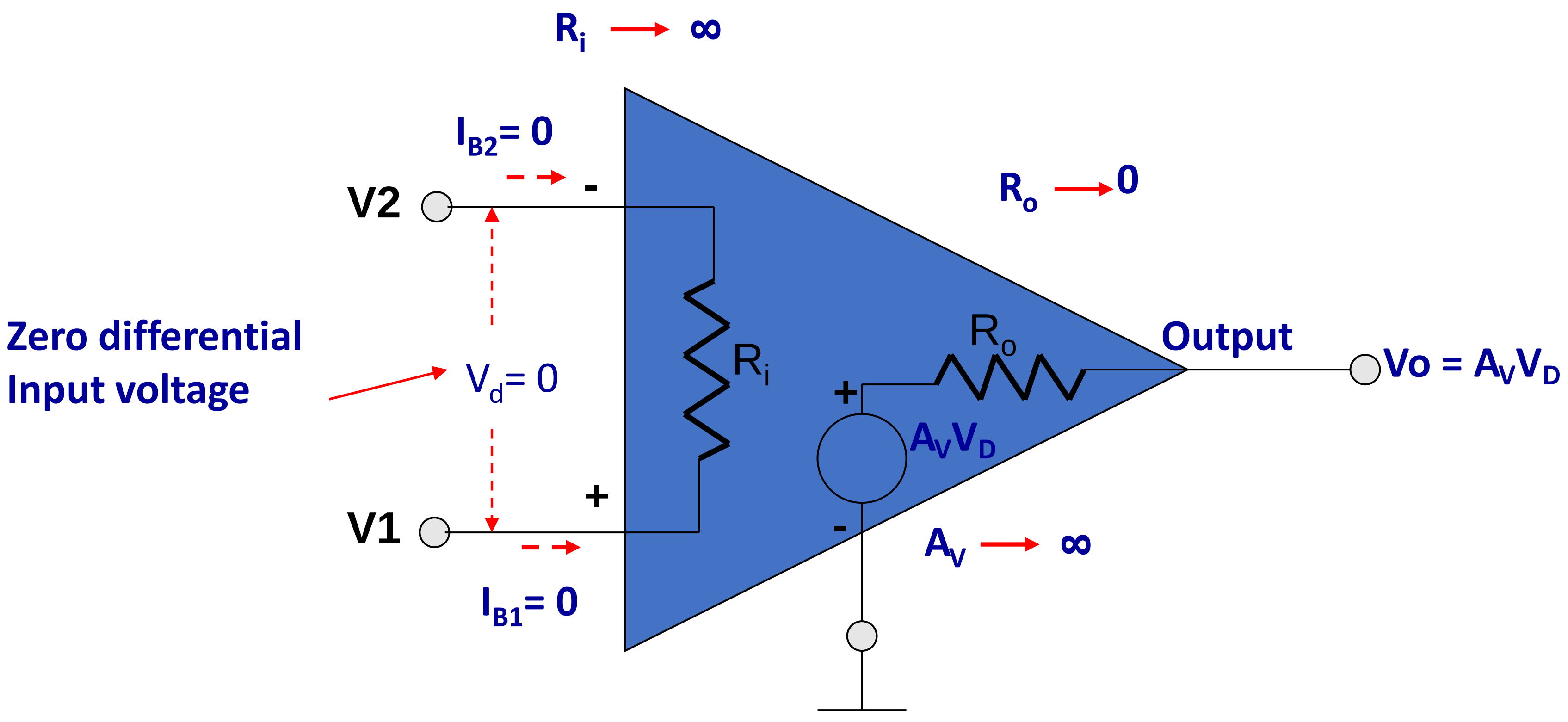
$\rightarrow$ slew rate $= \dfrac{dV}{dt}$

$= \dfrac{9-(-9)}{1\mu sec}$

$= \dfrac{18V}{1\mu sec}$.

slew rate $=$ 18 V/μsec.

The Ideal OP-AMP



8. Zero power supply rejection ratio (PSRR). (SVRR - Supply Voltage Rejection Ratio)

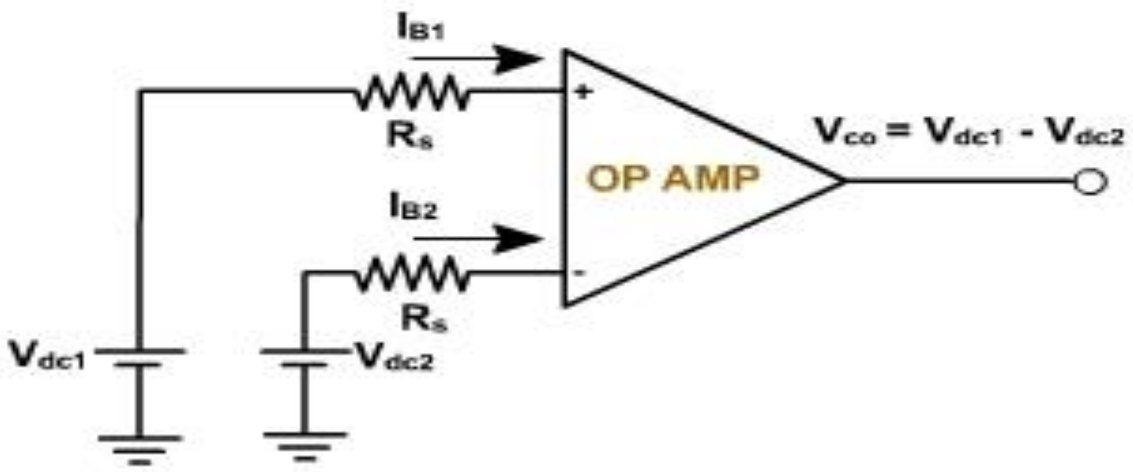
- PSSR is a parameter which specifies the degree of the dependence of the Op-amp output on the changes in power supply.
- For an ideal Op-amp, PSRR = 0. That means, the output voltage does not change due to fluctuation in supply voltage.

The Ideal OP-AMP

Input Offset Voltage (V_{io}) (Ideally, $V_{io} = 0$)

- It is the voltage which must be applied between two input terminals of op-amp to zero or null the output. ($V_{out} = 0$)
- It may be positive or negative.
- For a 741C OPAMP the maximum value of V_{io} is 6mV. It means a voltage ± 6 mV is required to one of the input to reduce the output offset voltage to zero.
- The smaller the input offset voltage the better the differential amplifier, because its transistors are more closely matched.

$$V_{io} = V_{dc1} - V_{dc2}$$



The Ideal OP-AMP

I_{B1}, I_{B2} } input currents to op-amp

Input Offset Current (I_{io}):

- It is the algebraic difference between the currents into the inverting and non-inverting terminals.

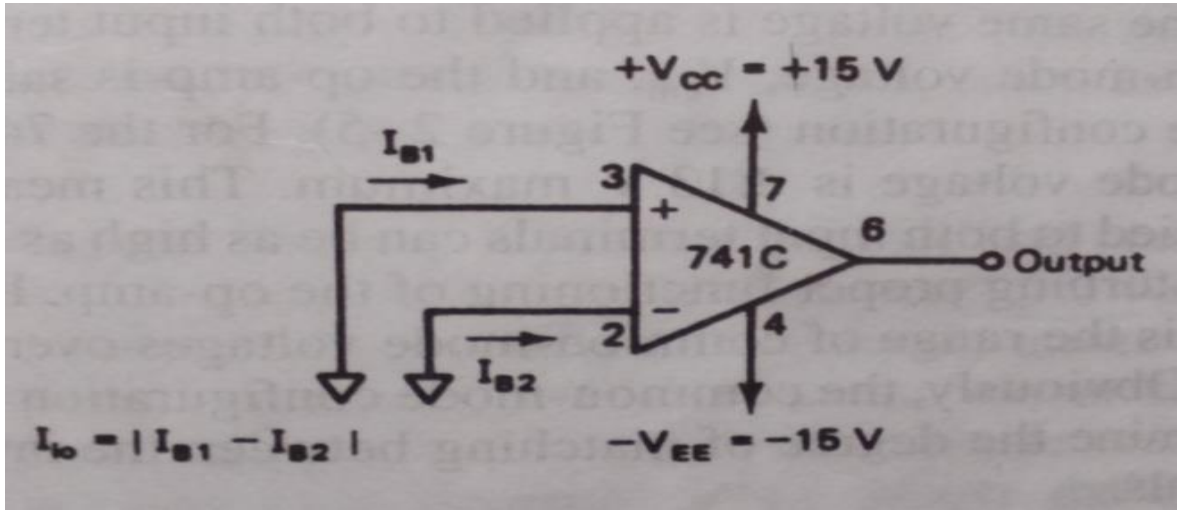
$$\boxed{I_{io}=|I_{B1}-I_{B2}|}$$

- The I_{io} for the 741C is 200nA maximum.
- As the matching between two input terminals is improved, the difference between I_{B1} and I_{B2} becomes smaller, i.e. the I_{io} value decreases further.
- For a precision OPAMP 741C, I_{io} is 6 nA.

Ideally, $I_{io}=0$

$I_{B1}=0$

$I_{B2}=0$



The Ideal OP-AMP

Input Bias Current (I_B):

- The input bias current I_B is the average of the current entering the input terminals of amplifier i.e.

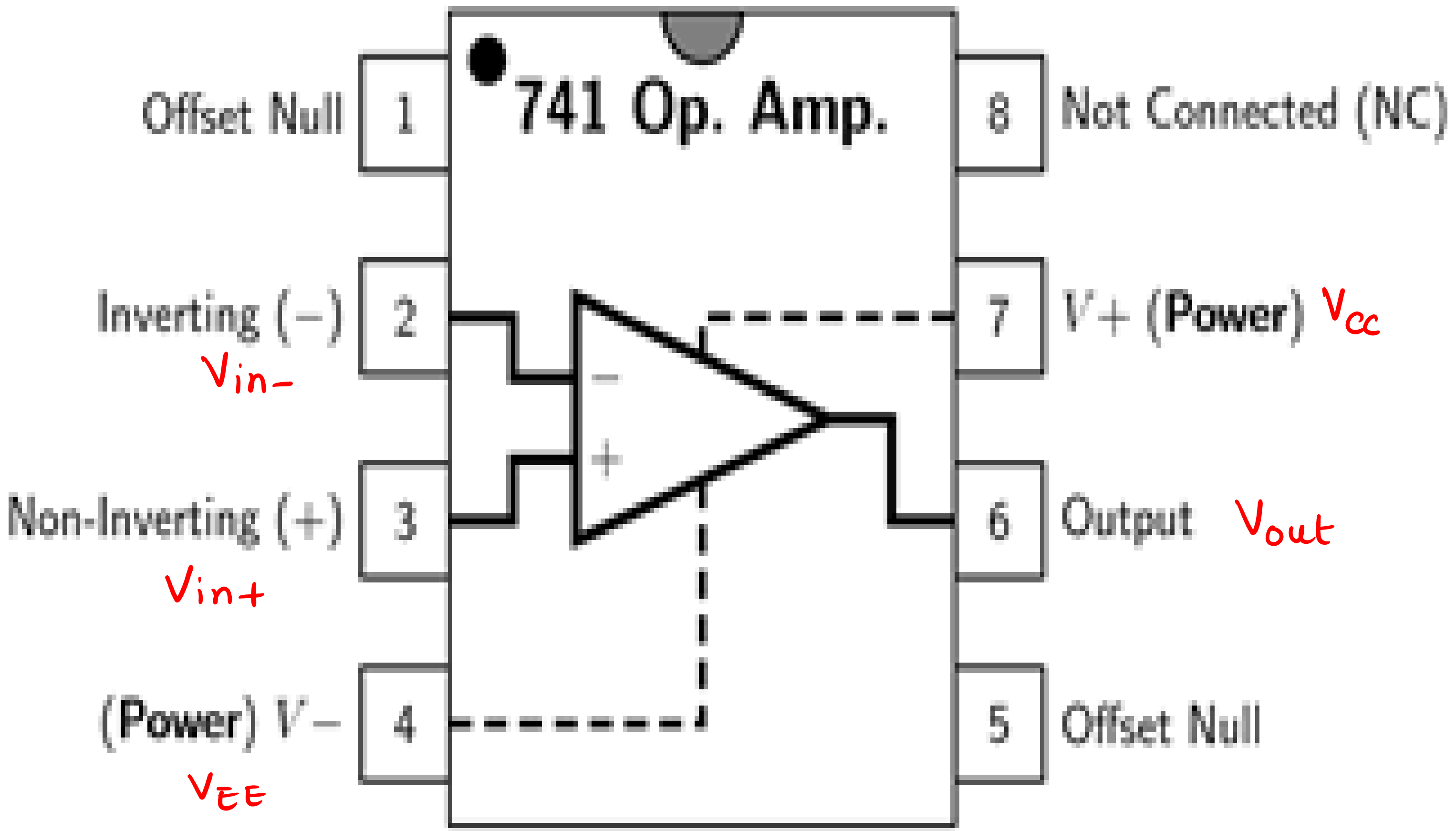
$$\boxed{I_B = (I_{B1} + I_{B2}) / 2}$$

- For 741C $I_{B(max)}$ = 700 nA and for precision 741C $I_B = \pm 7$ nA
- The input bias current is the dc current required by the inputs of the amplifier to properly operate the first stage.

Important Characteristics of OP-AMP IC 741

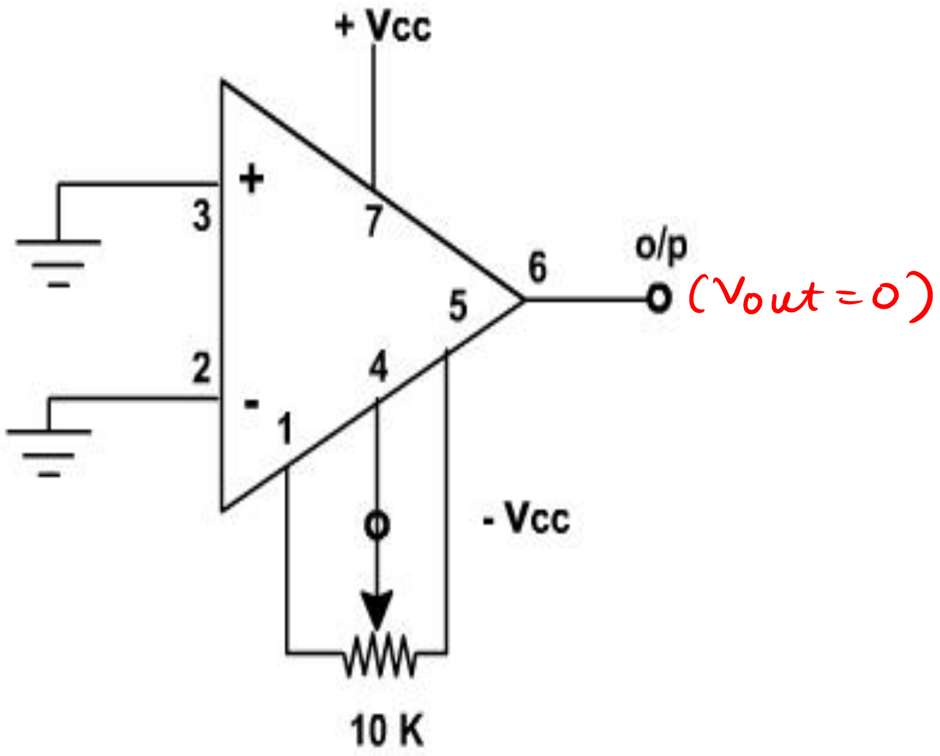
Sr. No.	Characteristics	Value for IC 741	Ideal value
1	Input resistance Ri	2 MΩ	∞
2	Output resistance Ro	75 Ω	0
3	Voltage gain Av	2×10^5	∞
4	Bandwidth BW	1 MHz	∞
5	CMRR	90 dB	∞
6	Slew rate S	0.5 V/µS	∞
7	Input offset voltage	2 mV	0
8	PSRR	150 µV/V	0
9	Input bias current	50 nA	0
10	Input offset current	6 nA	0

Pin Description of IC 741



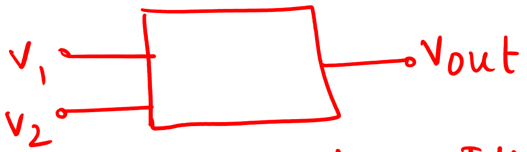
Offset Voltage Adjustment:

- 741 OPAMP have offset voltage null capability. Pins 1 and 5 are marked offset null for this purpose. It can be done by connecting 10 K ohm pot between pins 1 and 5.
- By varying the potentiometer, output offset voltage (with inputs grounded) can be reduced to zero volts. Thus, the offset voltage adjustment range is the range through which the input offset voltage can be adjusted by varying 10 K pot.
- For the 741 IC, the offset voltage adjustment range is ± 15 mV.



1 & 5 : offset null adjustment pins

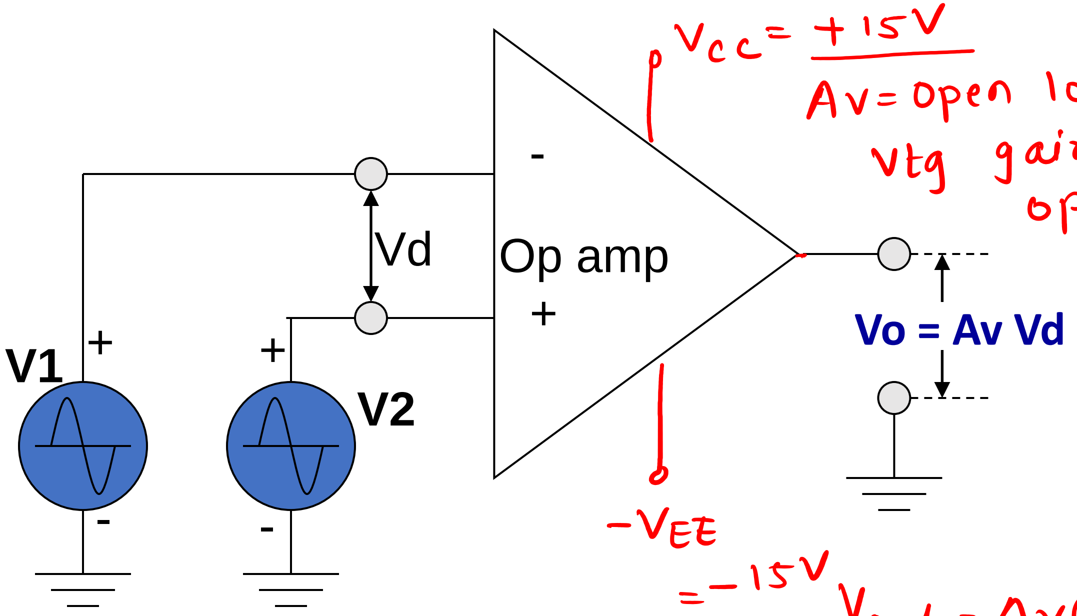
Open Loop Configuration of OP-AMP



↓ No f/b → open loop

The meaning of open loop operation is that there is absolutely no feedback present from the output to input.

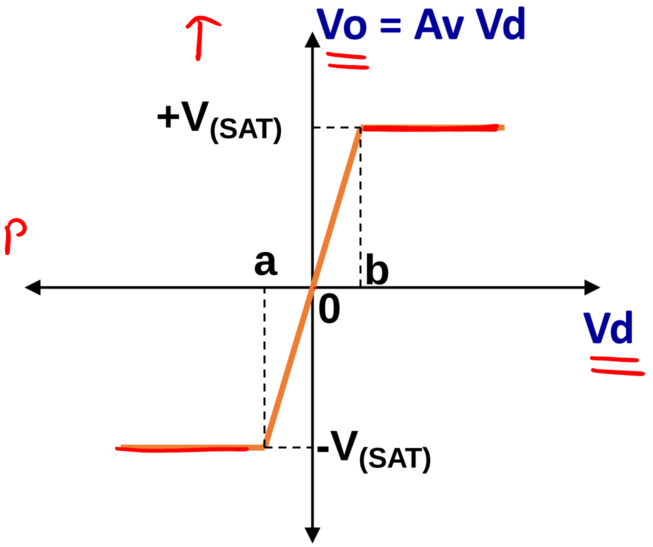
Example:
$A_v = 10^3$
$V_1 = 2V$
$V_2 = 1V$
$V_o = A_v . V_d$
$= 10^3 (2-1)$
$= 10^3 V$
$\underline{V_o = 15V}$



A_v = open loop vtg gain of op-amp

$V_{out} = A_v(V_d)$
$= A_v(V_1 - V_2)$

V(saturation)



$V_{sat} = V_{cc} \pm 2V$

$\pm V_{sat} = \pm V_{cc}$

Open Loop Configuration of OP-AMP

$V_1 = 30\mu V$

$V_2 = 25\mu V$

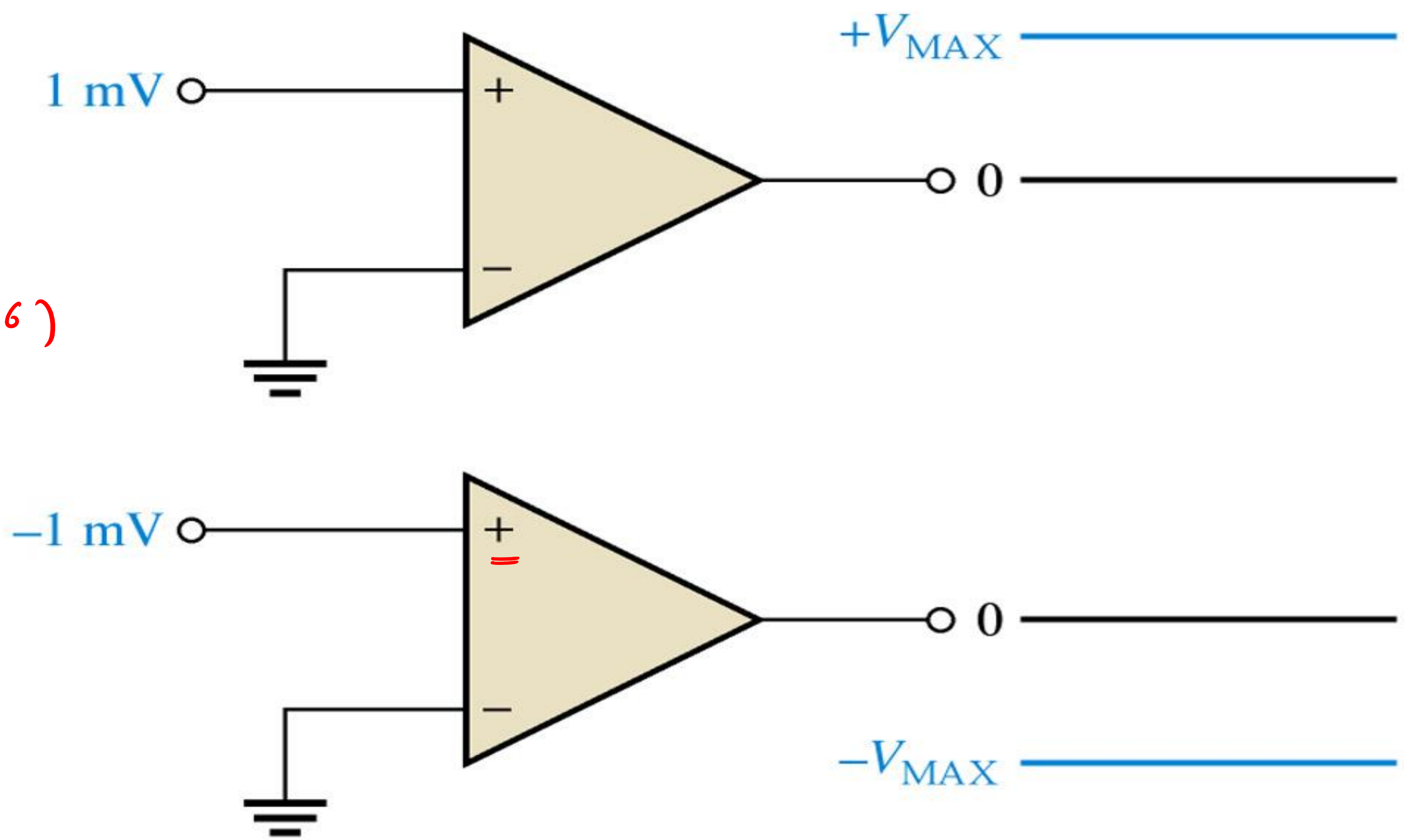
$A_v = 10^3$

$V_o = A_v . V_d$

$= 10^3 (5 \times 10^{-6})$

$= 5 \times 10^{-3} V$

$= 5 mV$



$+V_{sat}$

V_{cc}

$-V_{sat}$

$-V_{EE}$

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Why Op-amp not used as an amplifier in the open loop configuration ?

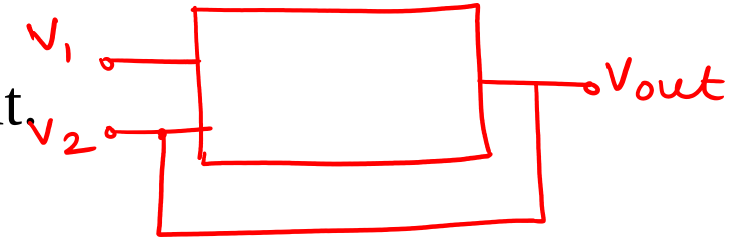
Large Av

(output is limited by supply vtg)

- Due to very large open loop gain, distortion is introduced in the amplified output signal.
- The open loop gain does not remain constant, it varies with change in temperature and power supply.
- For this reason, the Op-amp is not used in practice as an amplifier.
- **However, the Op-amp in open loop configuration is used in application such as comparator.**

Close Loop Configuration of OP-AMP

- In the closed loop configuration, some kind of "feedback" is introduced in the circuit.
- A part of output is returned back or fed back to the input.



Feedback
↓
closed loop.

Some part of the o/p is fed back to the i/p.

Types of feedback

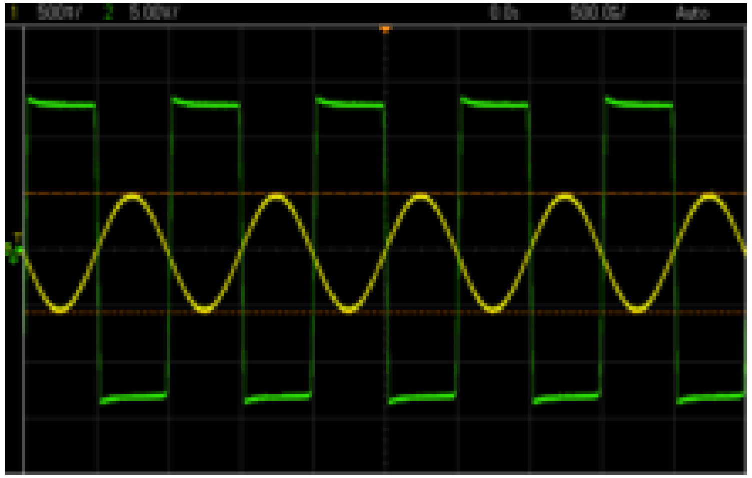
- Positive feedback or Regenerative feedback
- Negative feedback or Degenerative feedback.

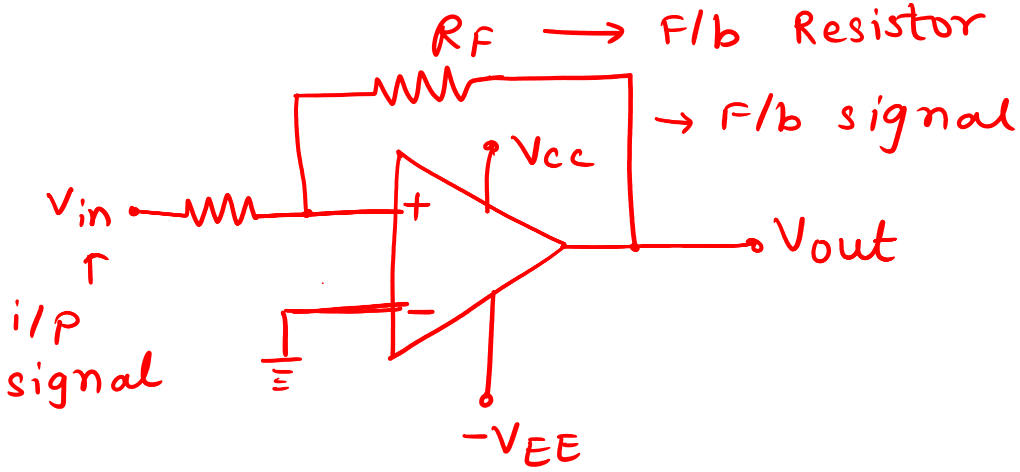
Positive Feedback or Regenerative Feedback

(0° phase shift)

- If the feedback signal and the original input signal are in phase with each other then it is called as the positive feedback.

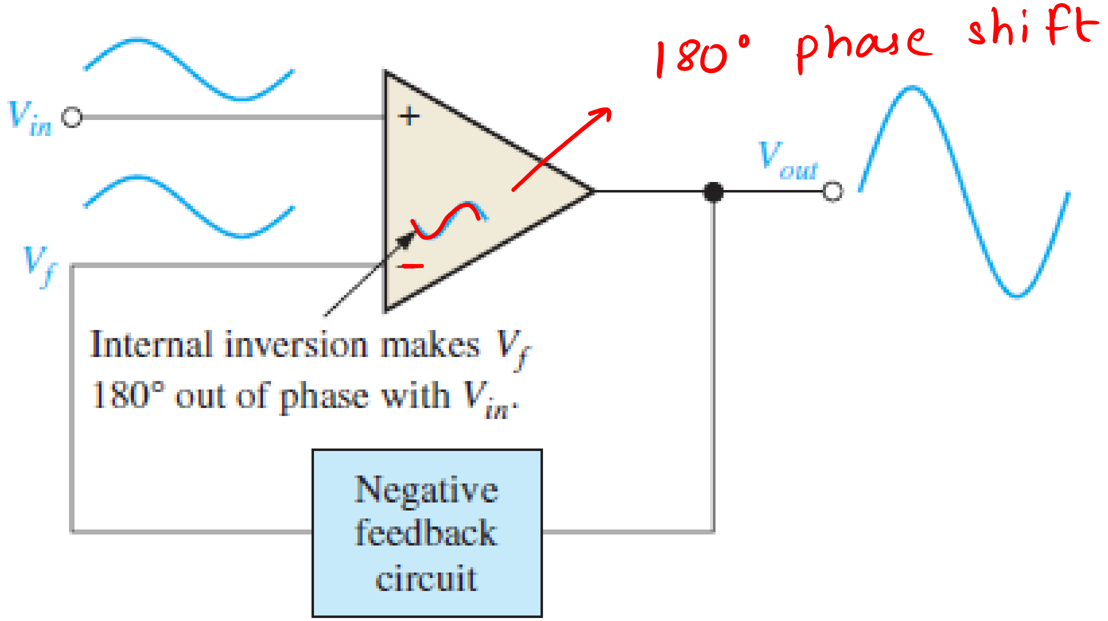
- Positive feedback is used in the application such as **"Oscillators" and Schmitt triggers or regenerative comparators.**





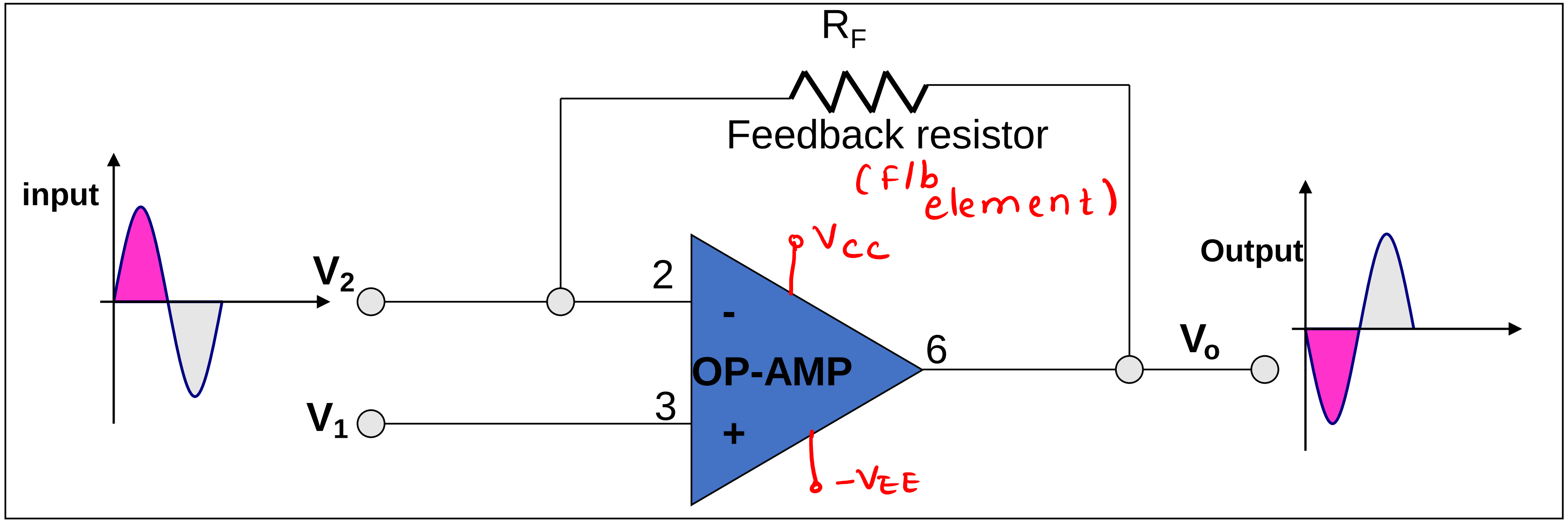
Negative Feedback or Degenerative Feedback

- If the signal is fed back to the input and the original input signal are 180^0 out of phase, then it is called as the negative feedback.
- In the application of **Op-amp as an amplifier**, the negative feedback is used.



Negative Feedback or Degenerative Feedback

- In the amplifier circuits using Op-amp, a feedback resistor RF is connected between the output and inverting terminal as shown in figure to introduced a negative feedback.
- As the voltages V_2 and V_O are 180^0 out of phase, a fraction of output voltage fed back to the input via R_F will be 180^0 out of phase with the input.

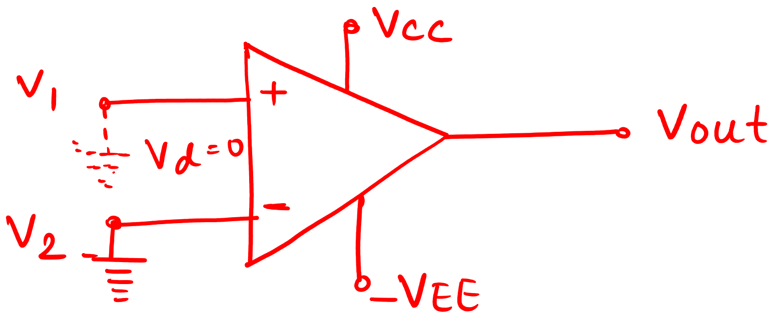


Advantages of Negative Feedback

Negative feedback is used in the amplifier circuits as they provide the following improvements in the operation of an amplifier:

- It stabilizes the gain. (Reduces open loop gain) → Gain depends on R_F & R_1 (i/p resistor)
- Reduces the distortion. (Gain is reduced)
- Increases the bandwidth. (Gain × BW product is constant)
- Reduces the effects of variation in temperature and supply voltage on the output of the Op-amp.

Virtual Ground / Virtual short :



$$V_{out} = A_v(V_d) = A_v(V_1 - V_2)$$

Ideally, $A_v = \infty$

$$A_v = \frac{V_{out}}{V_d}$$

To make $A_v = \infty$,

$$V_d = 0$$

$$V_1 - V_2 = 0$$

$$V_1 = V_2$$

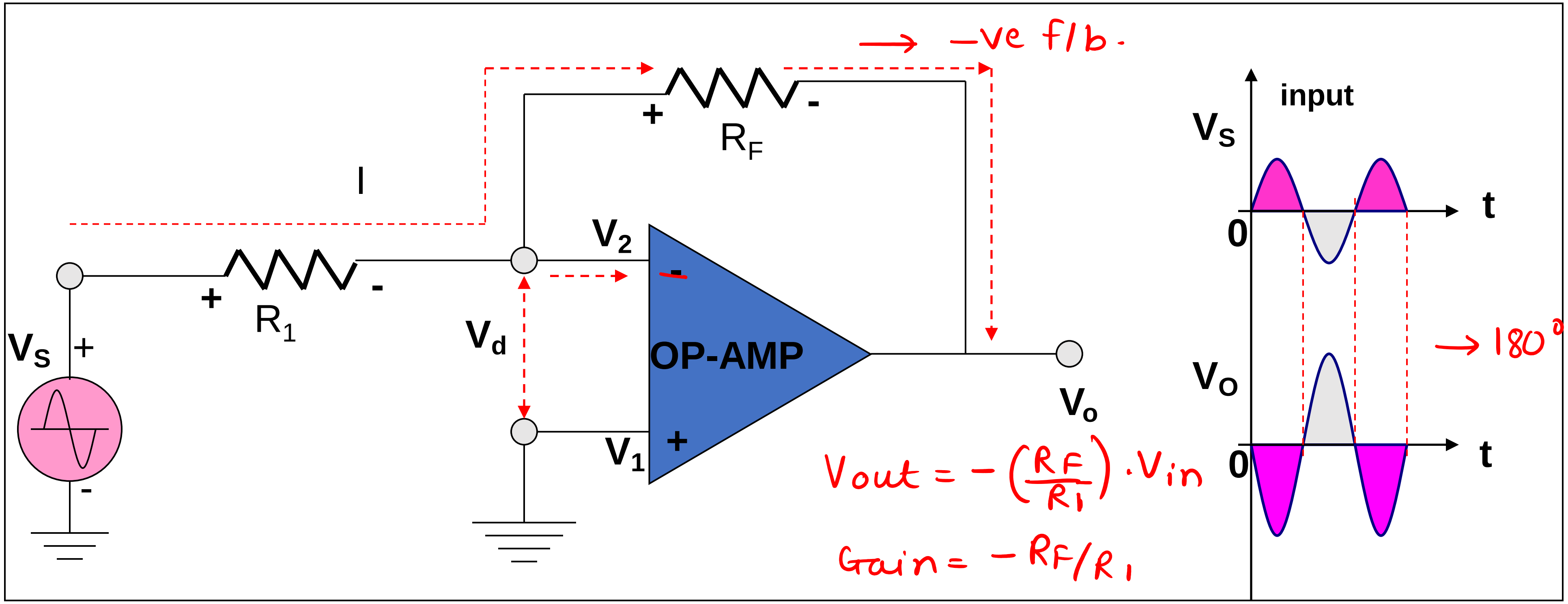
If $V_2 = 0$

V_1 is assumed to be at ground potential.

$\Downarrow$

Both the i/ps V_1 and V_2 are considered to be at same potential. ($V_d = 0$).

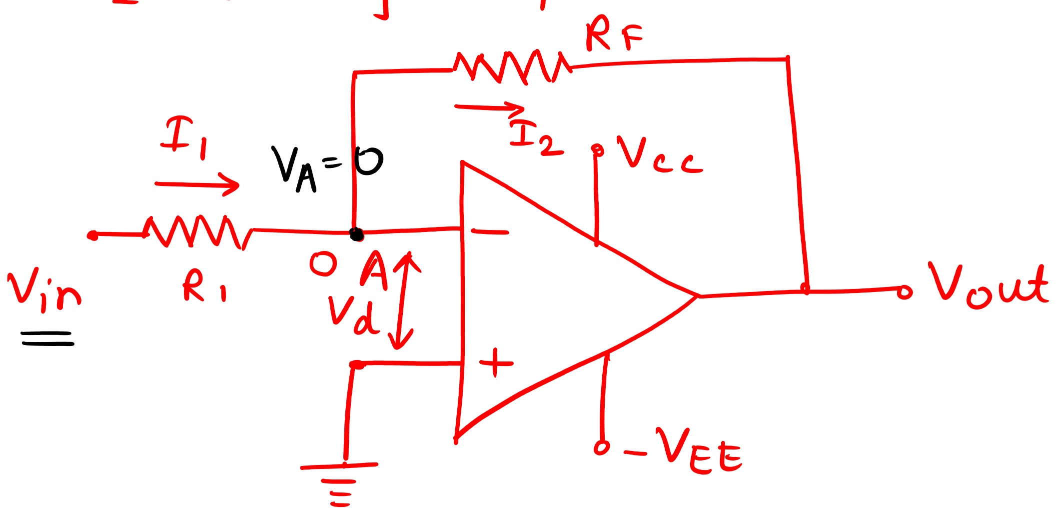
The Inverting Amplifier



- Expression for the closed loop voltage gain (A_{VF})
  $A_{VF} = - R_F / R_1$

- The negative sign indicates that there is a phase shift of 180^0 between the input and output voltages.

Inverting Amplifier:



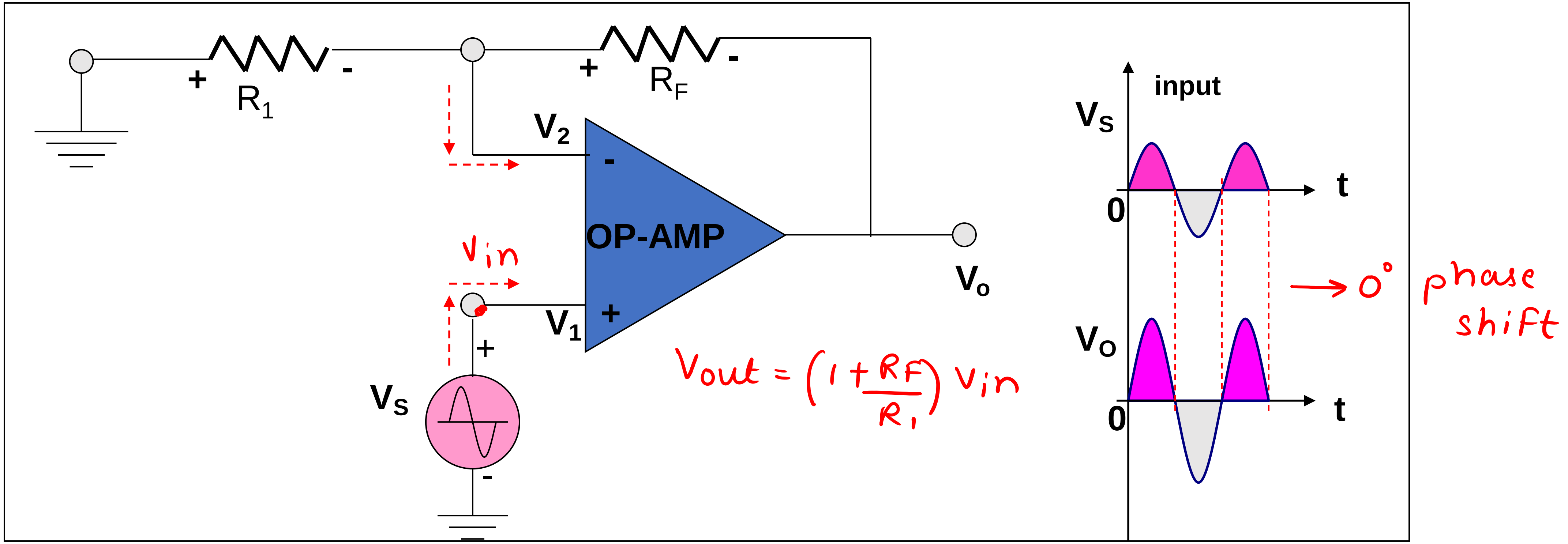
$V_A = 0$ —— (virtual ground)

$$\frac{V_{in} - 0}{R_1} = \frac{0 - V_{out}}{R_F}$$

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

$$\boxed{V_{out} = \frac{-R_F}{R_1} \cdot V_{in}}$$

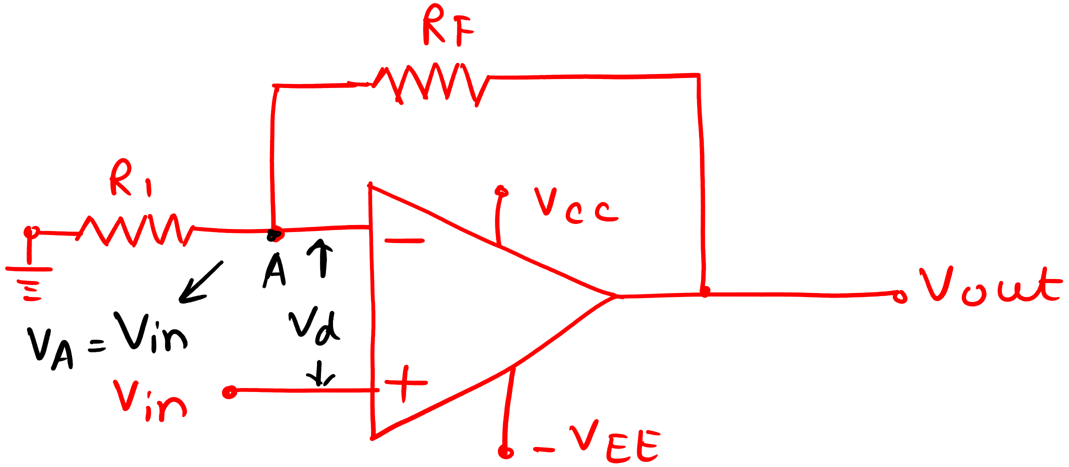
The Non-Inverting Amplifier



- Expression for the closed loop voltage gain (A_{VF})

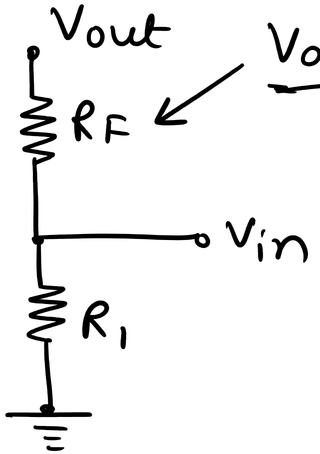
$$A_{VF} = 1 + \frac{R_F}{R_1}$$

Non-inverting Amplifier:



According to virtual ground,

$V_A = V_{in} \quad \ldots \quad (V_d = 0)$



Voltage divider,

$$V_{in} = \left(\frac{R_1}{R_1 + R_F}\right) V_{out}$$

$$V_{out} = \left(\frac{R_1 + R_F}{R_1}\right) V_{in}$$

$$V_{out} = \left(1 + \frac{R_F}{R_1}\right) V_{in}$$

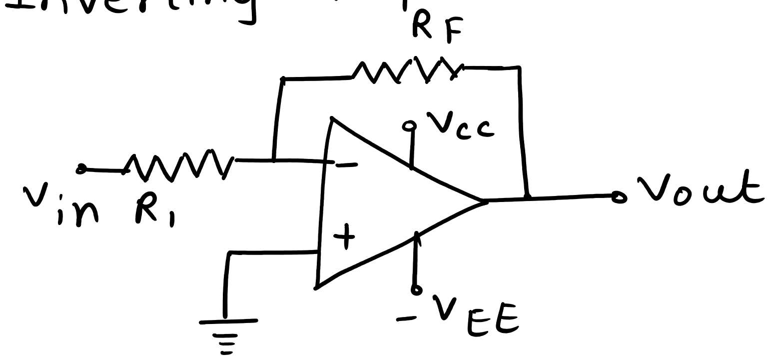
$$\frac{0 - V_{in}}{R_1} = \frac{V_{in} - V_{out}}{R_F}$$

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

$$\frac{V_{in}}{R_1} + \frac{V_{in}}{R_F} = \frac{V_{out}}{R_F}$$

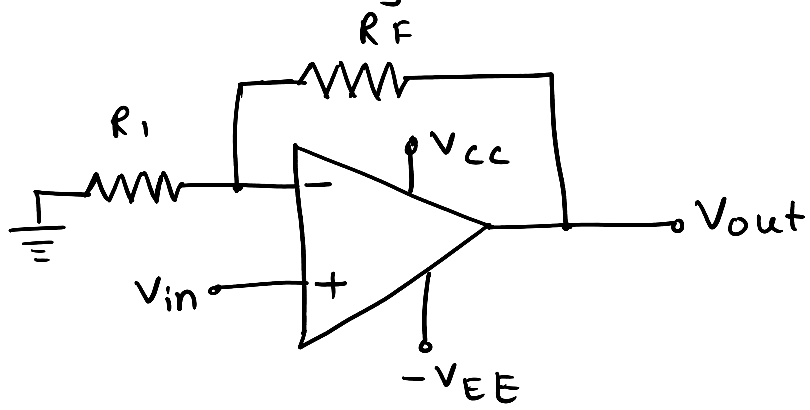
$$\boxed{V_{out} = \left(1 + \frac{R_F}{R_1}\right) V_{in}}$$

* Inverting Amplifier:



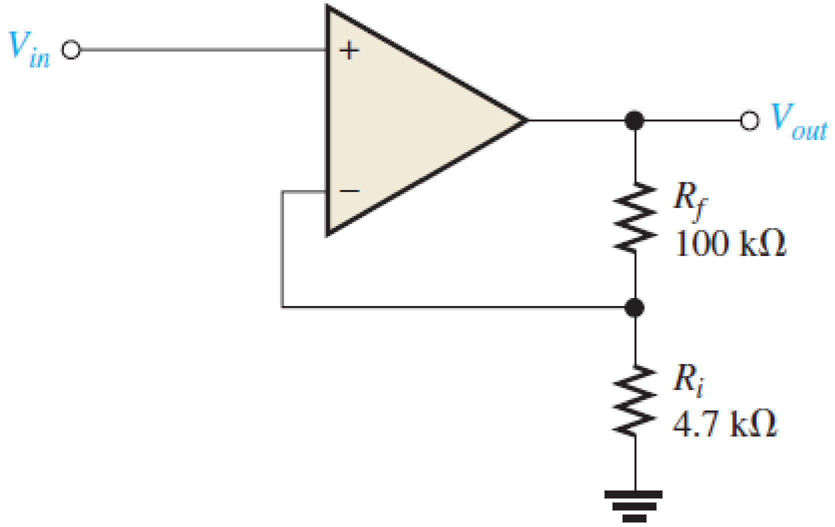
$$V_{out} = \frac{-R_F}{R_1} \cdot V_{in}$$

* Non-inverting Amplifier:



$$V_{out} = \left(1 + \frac{R_F}{R_1}\right) V_{in}$$

1> Determine the closed-loop voltage gain of the amplifier.



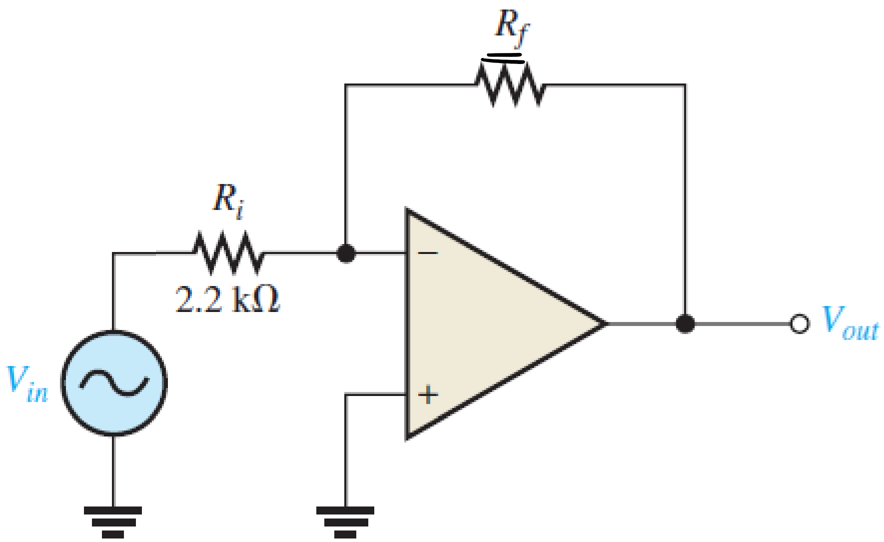
→ $V_{out} = \left(1 + \frac{R_F}{R_1}\right) V_{in}$

Closed loop gain $= 1 + \frac{R_F}{R_1}$

$= 1 + \frac{100k}{4.7k}$

$= 22.3$

2> Given the op-amp configuration in, determine the value of *Rf* required to produce a closed-loop voltage gain of -100.



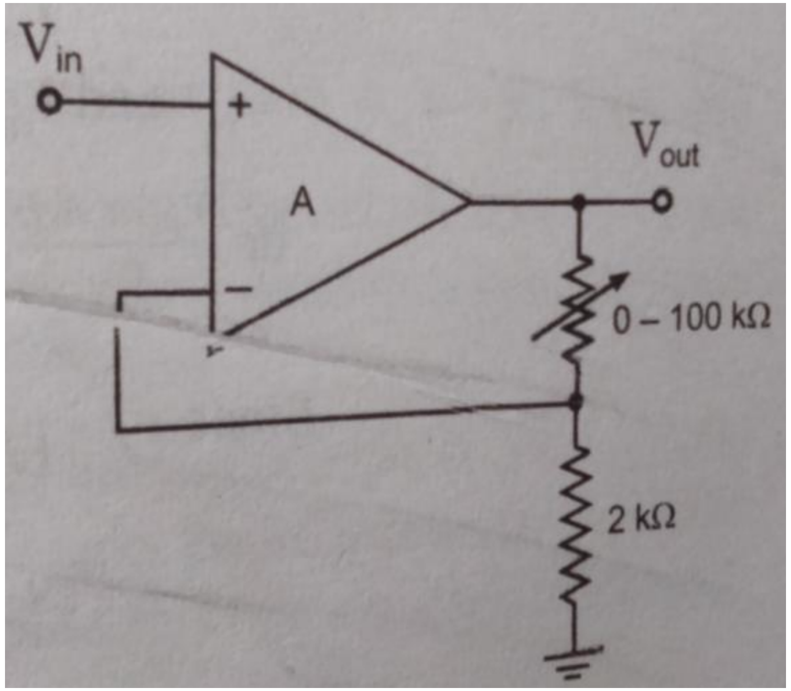
→ Closed loop gain $= -100$

$-\frac{R_F}{R_1} = -100$

$R_F = 100 \times R_1$

$\therefore R_F = 220k\Omega$

The variable resistance varies from 0 to 100KΩ. Find the maximum and minimum closed loop voltage gain.



Solution:

R1=2K Ω, Rf(min)=0,Rf(max)= 100KΩ

A=(1+Rf/R1)

A_{max} = (1+100/2)

A_{max} =51

A_{min} =(1+0/2)

A_{min} = 1

What is the range of the voltage gain adjustment in the given circuit?

Solution:

$$Af = -Rf/R1$$

$$Af_{min} = -Rf/R1_{max}$$

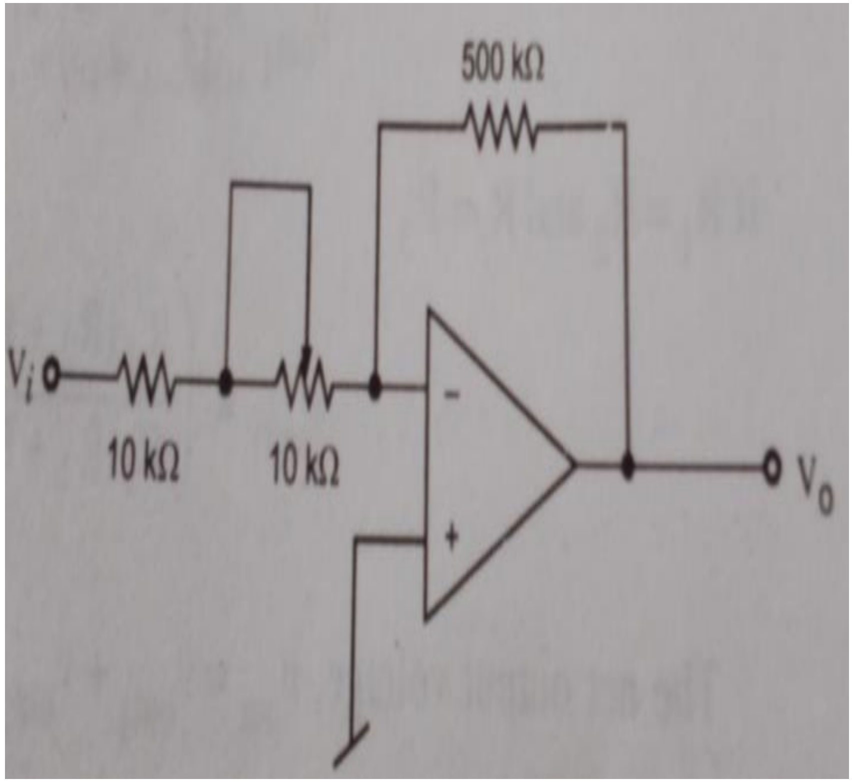
$$= -500K/(10K+10K)$$

$$\underline{Af_{min} = -25}$$

$$Af_{max} = -Rf/R1_{min}$$

$$= -500K/(10K)$$

$$\underline{Af_{max} = -50}$$



If the differential voltage gain and common mode voltage gain of Op-Amp are 50 dB and 10dB respectively. What is the value of CMRR?

→ $A_d = 50\,dB$

$A_c = 10\,dB$

$CMRR = ?$

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

$$CMRR(dB) = 20\log_{10}\left(\frac{A_d}{A_c}\right)$$

$$CMRR(dB) = A_d(dB) - A_c(dB)$$

$$= 50\,dB - 10\,dB$$

$$= 40\,dB$$

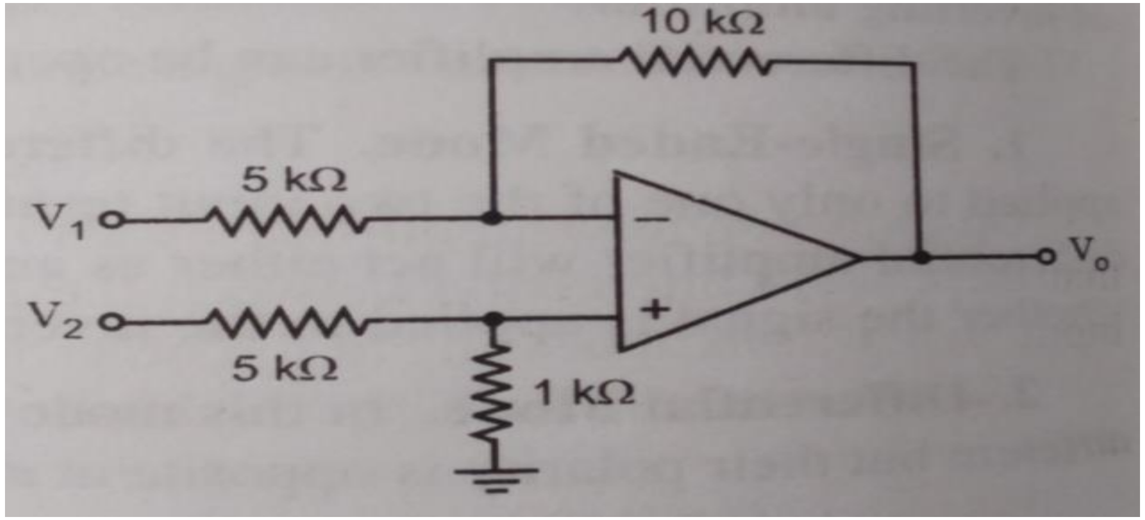
$$40\,dB = 20\log_{10}(CMRR)$$

$$CMRR = 10^2$$

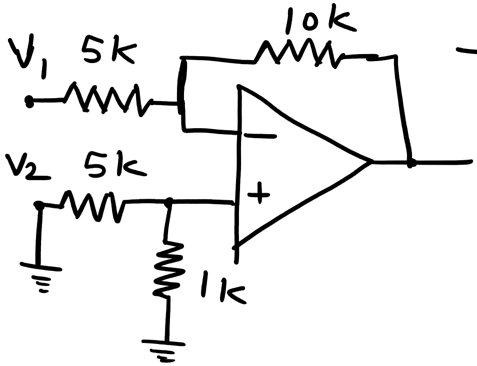
$$= 100.$$

Find the output voltage of the op-amp shown in figure.

$$V_{out} = V_{o1} + V_{o2} = -2V_1 + \frac{1}{2}V_2$$



1) To find V_{o1}, $V_2 = 0$



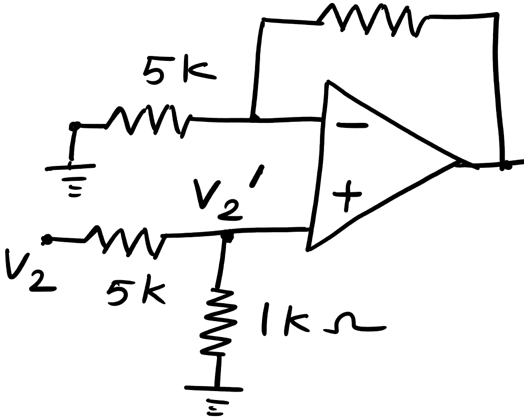
→ Inverting ampr

$$V_{o1} = \frac{-R_F}{R_1} \cdot V_1$$

$$= \frac{-10k}{5k} \cdot V_1$$

$$\boxed{\therefore V_{o1} = -2V_1}$$

2) To find V_{o2}, $V_1 = 0$



→ Non-inverting ampr

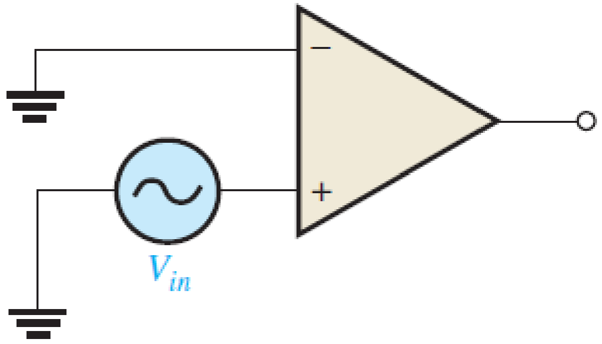
$$V_{o2} = \left(1 + \frac{R_F}{R_1}\right) V_2'$$

$$V_2' = \left(\frac{1k}{1k + 5k}\right) V_2 = \frac{1}{6} V_2$$

$$\therefore V_{o2} = \left(1 + \frac{10k}{5k}\right) \frac{1}{6} \cdot V_2 = \frac{3}{6} V_2 = \frac{1}{2} V_2$$

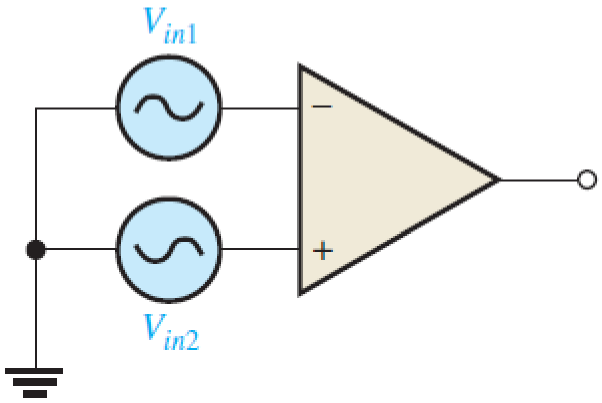
$$\boxed{\therefore V_{o2} = \frac{1}{2} V_2}$$

Modes of OP-AMP:



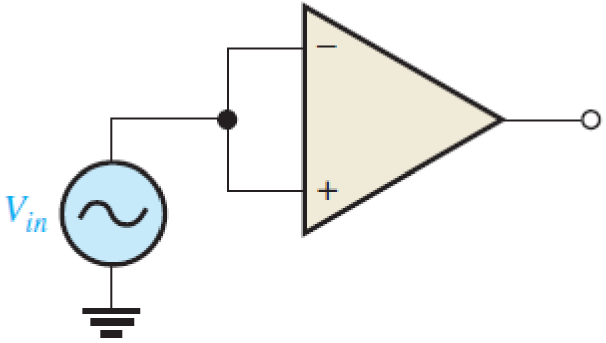
(a)

→ single ended input



(b)

→ Double ended input



(c)

→ common mode input

$V_1 = 675\,\mu V$

$V_2 = 665\,\mu V$

$CMRR = 80\,dB$

$A_d = 5 \times 10^5$

$\rightarrow$ $CMRR = 20\log_{10}\left(\frac{A_d}{A_c}\right)$

$CMRR = 10^4$

Now,

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

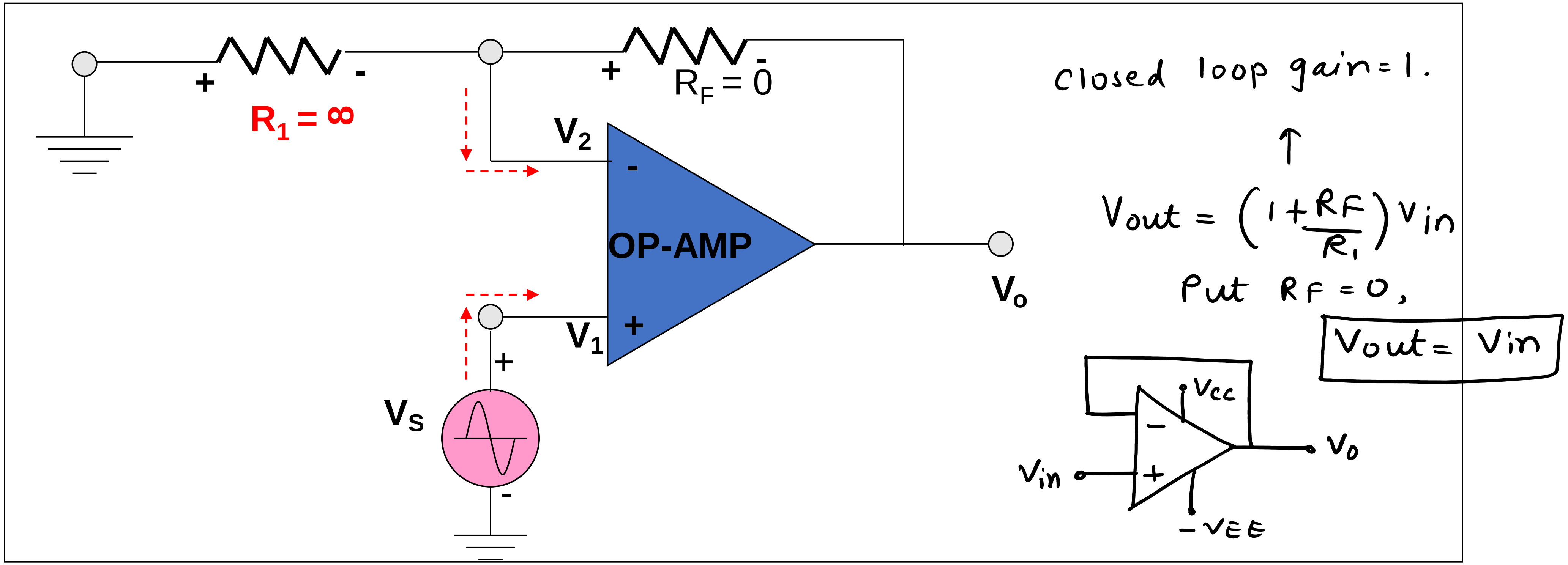
$10^4 = \frac{5 \times 10^5}{A_c}$

$\therefore A_c = 50$

$V_{out} = A_d(V_1 - V_2) + A_c\left(\frac{V_1 + V_2}{2}\right)$

$= 5.0335\,V$

The Voltage Follower (Unity Gain Buffer)



- When R1 is infinite and RF = 0 the non-inverting amplifier gets converted into a voltage follower or unity gain.

Acknowledgements

1. Electronic Devices, Thomas L. Floyd
2. Web Resources

Thank You..