Subject

Linear Integrated Circuits
(ELC 503)

DLIC Course Contents

- **Unit 1- Fundamentals of Operational Amplifier (IC-µA741C/LM351/LF 351)**
- **Unit 2- Linear Applications of Operational Amplifier**
- **Unit 3 - Non-Linear Applications of Operational Amplifier**
- **Unit 4 - Active Filter and Oscillators Using OP-Amp IC-741C**
- **Unit 4 - Data Converters:- D-A and A-D Converters, ADC 0808/0809, DAC 0808 and its interfacing**
- **Unit 5 - Specialized IC applications, IC-555 (Timer IC),IC-566 (VCO), IC-565 (PLL) LM 380 (power amplifier)**
- **Unit 6 – Regulators ICs 78XX, 79XX, LM 317, LM 337, IC 723**
- **Text Books- 1. Linear Integrated Circuits – D. Roy Choudhury , 4th edition**

2. Op-Amps & Linear ICs – Ramakanth A. Gayakwad , 4th ed 3.Design with operational amplifiers and analog Integrated Circuits Sergio Franco, 3rd ed.

Course Objective

- To teach fundamental principles of standard linear integrated circuits.
- To develop a overall approach for students from selection of integrated circuits, study its specification, the functionality, design and practical applications.
- To teach the basic concepts in the design of electronic circuits using linear integrated circuits and their applications in the processing of analog signals.
- Also to introduce a few special function Integrated Circuits such as Regulator ICs, Waveform generator Ics etc.

Course Outcome

CO1	**Demonstrate an understanding of fundamentals of integrated circuits.**
CO2	Analyze the various applications and circuits based on particular linear integrated circuits.
CO3	Select and use an appropriate integrated circuit to build a given application.
CO4	Data converter study & analysis of data coverter. ADC 0808/0809, DAC 0808 and its interfacing
CO5	Design an application with the use of integrated Circuit
CO6	Design an application with Regulator ICs

Unit 1 : 1.1 Introduction to IC

Q1. What is a Integrated Circuits?

Q2. Where do we use an Integrated Circuit?

Q3. Why do you prefer an Integrated Circuit to the circuits made by interconnecting discrete components?

Ans :- An integrated circuit (IC) is a miniature ,low cost electronic circuit consisting of active and passive components fabricated together on a single crystal of silicon.

The active components are transistors and diodes and passive components are resistors and capacitors.

ICs 14 pin & 8pin

1.2 Chip size and Complexity

Invention of Transistor (Ge)	- 1947
Development of Silicon	- 1955-1959
Silicon Planar Technology	- 1959
First ICs, SSI (3- 30gates/chip)	- 1960
MSI (30-300 gates/chip)	- 1965-1970
LSI (300-3000 gates/chip)	-1970-1975
VLSI (More than 3k gates/chip)	- 1975

SSI	MSI	LSI	VLSI	ULSI
< 100 active Devices	100-1000 active devices	1000-100000 active devices	>100000 active devices	Over 1 million active devices
Integrated resistors, diodes & BJT's	BJT's and Enhanced MOSFETS	MOSFETS	8bit, 16bit Microprocessors	Pentium Microprocessors

1.3Advantages of Integrated Circuits

- Miniaturization and hence increased equipment density.
- Cost reduction due to batch processing.
- Increased system reliability due to the elimination of soldered joints.
- Improved functional performance.
- Matched devices.
- Increased operating speeds.
- Reduction in power consumption

In other words

- Small size
- Highly reliable
- Matched devices
- Fast speed

* Low power consumption
* Low cost
* Less weight
* Low supply voltages

1.4 Applications of an Integrated Circuit

- Communication
- Control
- Instrumentation
- Computer
- Electronics

Temperature Ranges

- Military temperature range: $- 55^0$ C to $+ 125^0$ C (-55o C to +85o C)
- Industrial temperature range : -20^0 C to $+ 85^0$ C (-40o C to +85o C)
- Commercial temperature range: 0^0 C to $+ 70^0$ C (0o C to +75o C)

1.5 Manufacturer’s Designation for Linear ICs

- Fairchild - µA, µAF
- National Semiconductor- LM,LH,LF,TBA
- Motorola- MC,MFC
- RCA- CA,CD
- Texas Instruments- SN
- Signetics - N/S,NE/SE
- Burr- Brown- BB

1.6 IC Packages Available

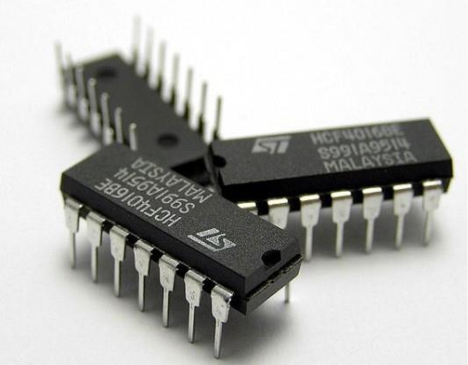
1. Metal can package

2. Dual-in-line package

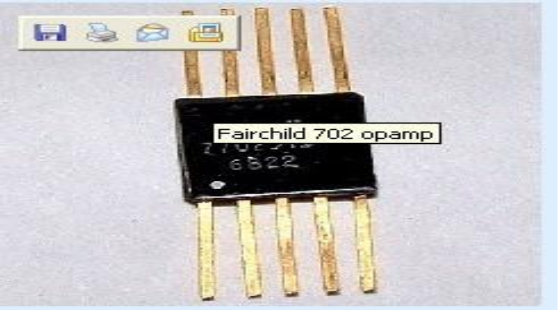
3. Ceramic flat package

1. Metal can package :- The metal sealing plane is at the bottom over which the chip is bounded, It is also called **transistor pack.**

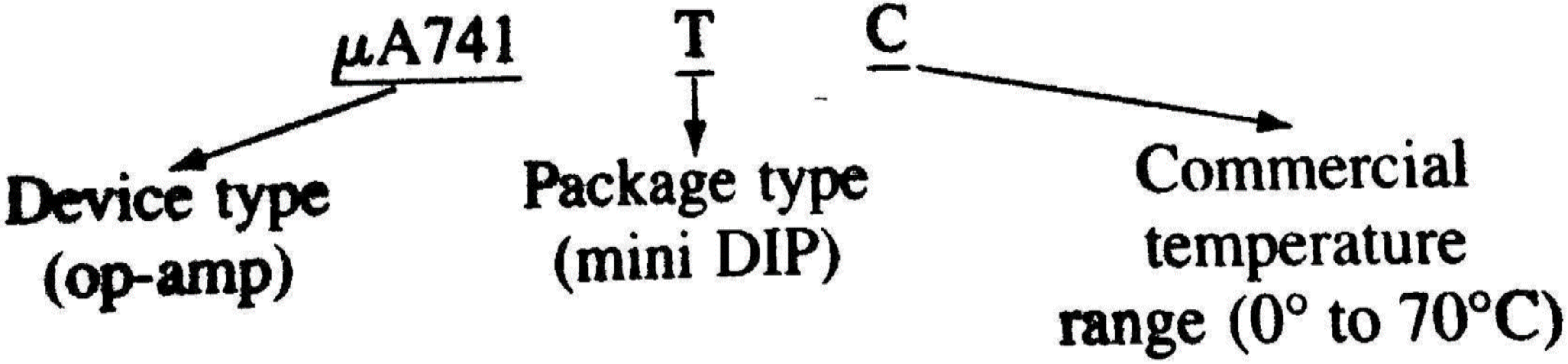
2. Dual-in-line package :- The chip is mounted inside a plastic or ceramic case. The 8 pin Dip is called **MiniDIP** and also available with 12, 14, 16, 20pins



3. Ceramic flat package :- The chip is enclosed in a rectangular ceramic case



Manufacture Designation



Features of IC-741 OP-AMP:-

- No External frequency compensation is required
- Short circuit Protection
- Off Set Null Capability
- Large Common mode and differential Voltage ranges
- Low Power Dissipation
- No-Latch up Problem

Selection of IC Packages

Type	Criteria
Metal Can Packages	1. Heat dissipation is important 2. For high power applications like power amplifiers, voltage regulators etc
DIP	1. For experimental or bread boarding purposes as easy to mount 2. If bending or soldering of the leads is not required 3. Suitable for printed circuit boards as lead spacing is more
Flat Pack	1 More reliability is required 2 Light in weight 3. Suited for airborne applications

1.7 Factors affecting selection of IC package

- Relative cost
- Reliability
- Weight of the package
- Ease of fabrication
- Power to be dissipated
- Need of external heat sink

Unit 1- 1.8 Introduction to Operational Amplifier

1.8.1 Introduction :

In this unit we study the basic structure of the operational amplifier (op-amp) and then analyze a typical Operational Amplifier circuit. We will also investigate the op-amp symbol, types of op-amp, different grades of op-amp, and op-amp development.

1.8.2 Operational Amplifier

Que. What is An Operational Amplifier

- An operational amplifier is a direct-coupled high-gain amplifier usually consisting of one or more differential amplifiers and usually followed by a level translator and an output stage.
- An operational amplifier is available as a single integrated circuit package
- The operational amplifier is a versatile device that can be used to amplify dc as well as ac input signals and was originally designed for computing such mathematical functions as addition, subtraction, multiplication, and integration.

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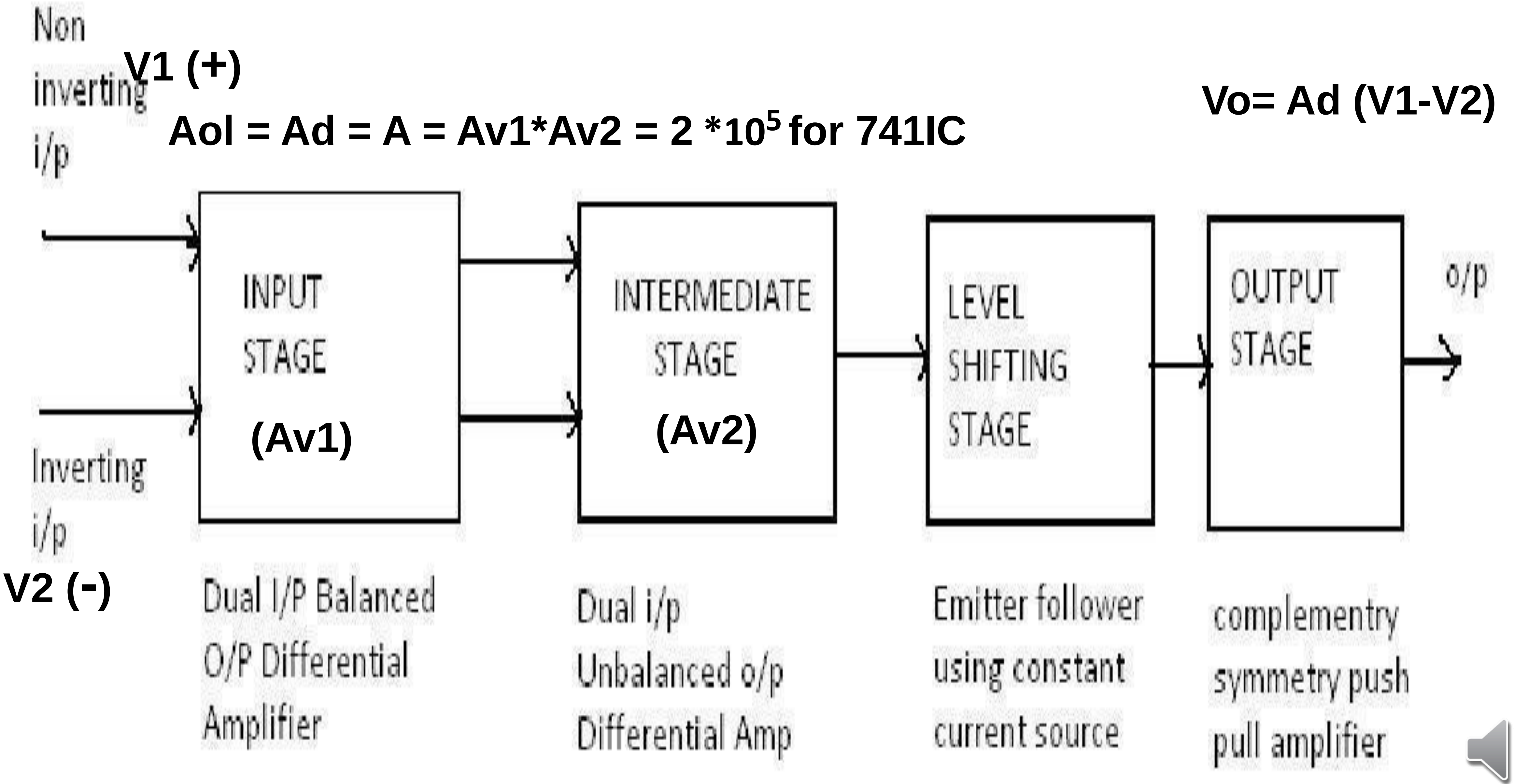
- Thus the name operational amplifier stems from its original use for these mathematical operations and is abbreviated to op-amp.
- With the addition of suitable external feedback components, the modern day op-amp can be used for a variety of applications, such as AC and DC signal amplification, Active Filters, Oscillators, Comparators, Regulators, Rectifiers and others.

1.8.3 : Block diagram of op amp



Non inverting i/p

V1 (+)

Aol = Ad = A = Av1*Av2 = $2 * 10^5$ for 741IC

Vo= Ad (V1-V2)

Inverting i/p

V2 (-)

INPUT STAGE **(Av1)**

Dual I/P Balanced O/P Differential Amplifier

INTERMEDIATE STAGE **(Av2)**

Dual i/p Unbalanced o/p Differential Amp

LEVEL SHIFTING STAGE

Emitter follower using constant current source

OUTPUT STAGE

complementry symmetry push pull amplifier

o/p

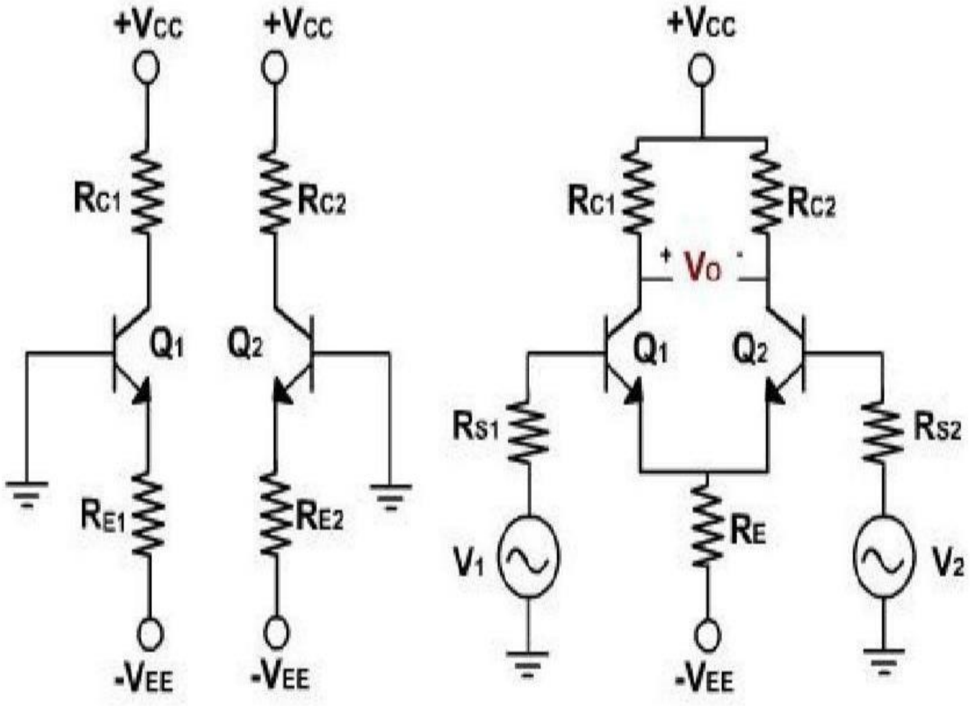
Internal Circuit :

- The operational amplifier is a direct-coupled high gain amplifier usable from 0 to over 1MHz
- to which feedback is added to control its overall response characteristic i.e. gain and bandwidth.
- The op-amp exhibits the gain down to zero frequency.
- The internal block diagram of an op-amp is shown in the fig 1.3.
- The input stage is the dual input balanced output differential amplifier. This stage generally provides most of the voltage gain of the amplifier
- and also establishes the input resistance of the op-amp.
- The intermediate stage is usually another differential amplifier, which is driven by the output of the first stage.
- On most amplifiers, the intermediate stage is dual input, unbalanced output.

- Because of direct coupling, the dc voltage at the output of the intermediate stage is well above ground potential.
- Therefore, the level translator (shifting) circuit is used after the intermediate stage downwards to zero volts with respect to ground.
- The final stage is usually a push pull complementary symmetry amplifier output stage.
- The output stage increases the voltage swing and raises the ground supplying capabilities of the op-amp. A well designed output stage also provides low output resistance.
- Ideally, the output voltage is zero when the two inputs are equal. When v1 is greater then v2 the output voltage with the polarity shown appears. When v1 is less than v2, the output voltage has the opposite polarity.

Differential Amplifier

- Differential amplifier is a basic building block of an op-amp.
- The function of a differential amplifier is to amplify the difference between two input signals.
- The two transistors Q1 and Q2 have identical characteristics.
- The resistances of the circuits are equal, i.e. RE1 = R E2, RC1 = R C2 and the magnitude of +VCC is equal to the magnitude of -VEE. These voltages are measured with respect to ground.



$$V_0 = A_d (V_1 - V_2)$$

$$A_d = 20 \log_{10} (A_d) \text{ in dB}$$

$$V_c = \frac{(V_1 + V_2)}{2}$$

$$\text{CMRR} = \rho = \left| \frac{A_d}{A_c} \right|$$

Fig: -Differential Amplifier & its Mathematical Analysis

- To make a differential amplifier, the two circuits are connected as shown in fig.
- The two +VCC and -VEE supply terminals are made common because they are same.
- The two emitters are also connected and the parallel combination of RE1 and RE2 is replaced by a resistance RE.
- The two input signals v1& v2 are applied at the base of Q1 and at the base of Q2.
- The output voltage is taken between two collectors. The collector resistances are equal and therefore denoted by RC = RC1 = RC2.
- Ideally, the output voltage is zero when the two inputs are equal. When v1 is greater then v2 the output voltage with the polarity shown appears. When v1 is less than v2, the output voltage has the opposite polarity.

Vo= Ad (V1-V2) ------- Very important relation

Characteristics of Differential Amplifier and Equations:--

1.Differential voltage gain is very High 2. Differential Input resistance is very High

3. Output resistance is very Low 4. CMRR is High

$$V_o = V_{c2} - V_{c1}$$
$$= -R_C i_{C2} - (-R_c i_{c1}$$
$$= R_C(i_{C1} - i_{c2})$$
$$= R_C(i_{e1} - i_{e2})$$

$$V_o = R_C\left\{\frac{(r_e + R_E)V_1 - R_E V_2}{(r_e' + R_E)^2 - R_E^2} - \frac{(r_e + R_E)V_2 - R_E V_1}{(r_e' + R_E)^2 - R_E^2}\right\}$$
$$= \frac{R_C(V_1 - V_2)(r_e' - 2R_E)}{r_e'(r_e' + 2R_E)}$$
$$V_o = \frac{R_C}{r_e'}(V_1 - V_2) \text{............} E(1)$$

$$R_{i2} = \left.\frac{V_2}{i_{b2}}\right|_{v_1=0}$$
$$= \left.\frac{V_2}{i_{e2}/\beta}\right|_{v_1=0}$$
$$R_{i2} = 2\beta r'_e \qquad (E-4)$$

Ri1=Ri2= 2βre

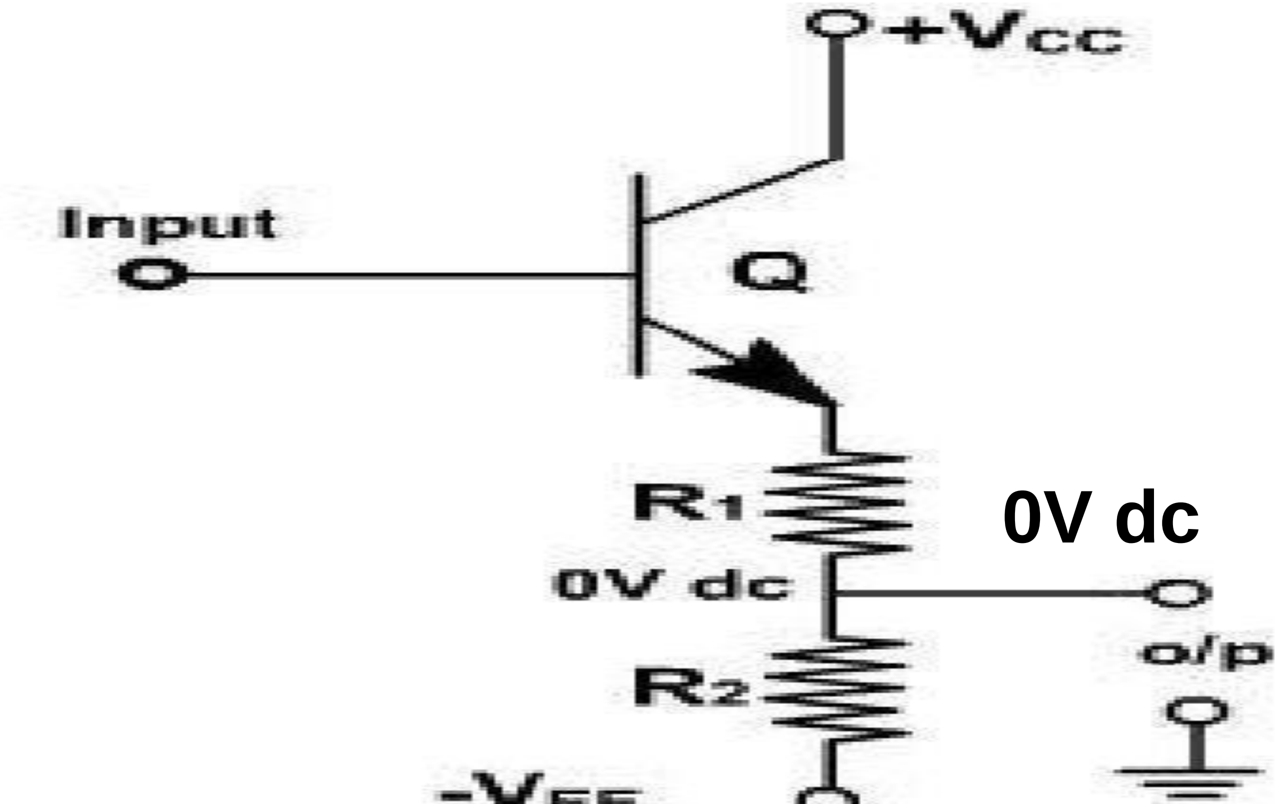
RO1 = RO2 = RC

Vo /(V1-V2)= Aol = Ad =A = Rc /re’

Level Translator

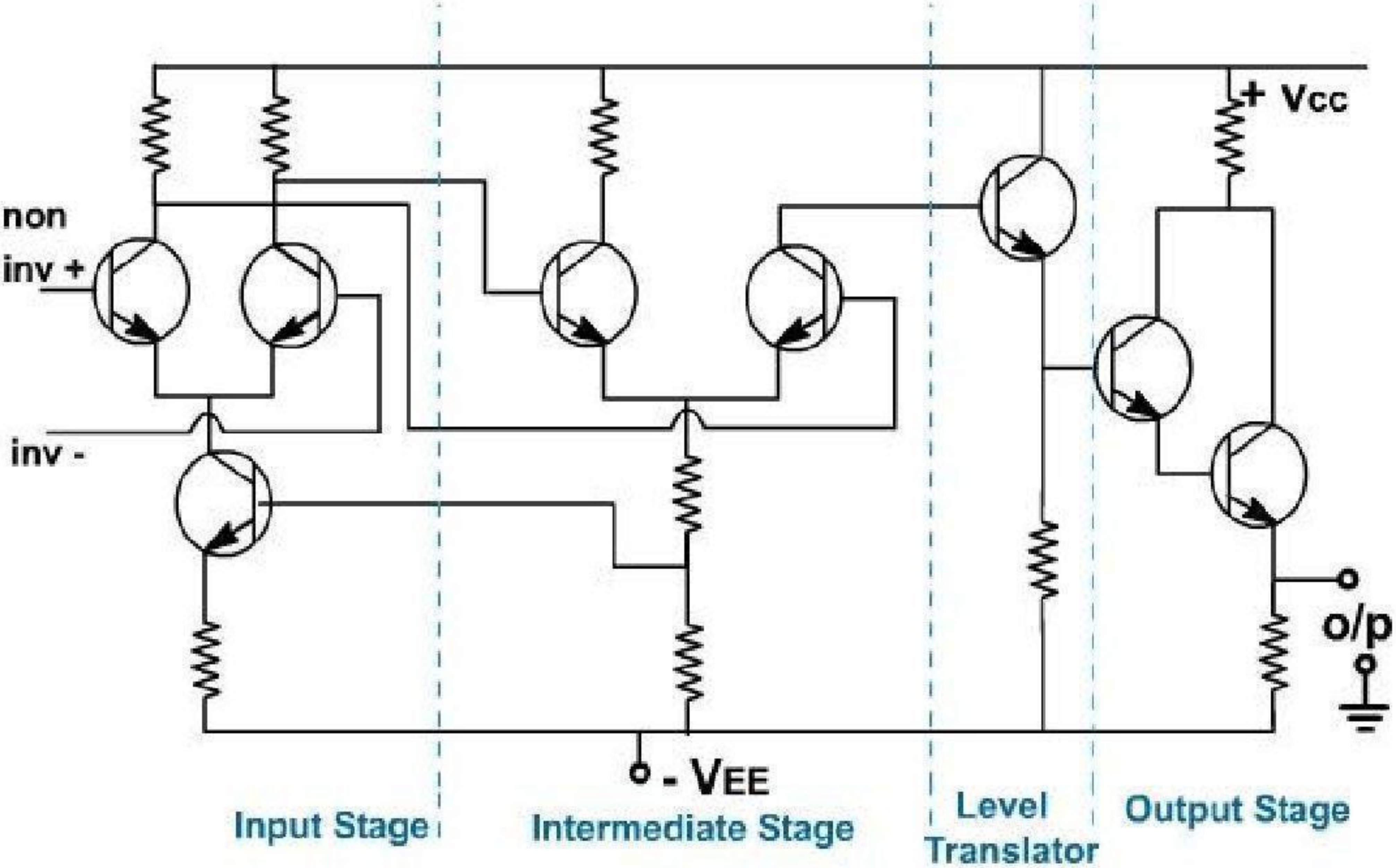
- Because of the direct coupling the dc level at the emitter rises from stages to stage. This increase in dc level tends to shift the operating point of the succeeding stages and therefore limits the output voltage swing and may even distort the output signal.
- To shift the output dc level to zero, level translator circuits are used. An emitter follower with voltage divider is the simplest form of level translator as shown in fig. Thus a dc voltage at the base of Q produces 0V dc at the output. It is decided by R1 and R2. Instead of voltage divider emitter follower either with diode current bias or current mirror bias as shown in fig may be used to get

  better results.

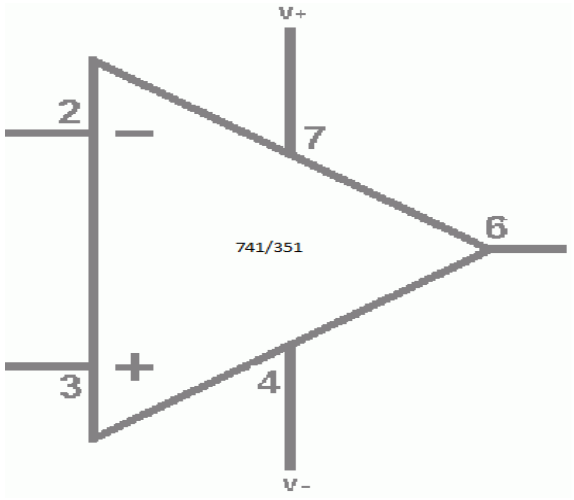


- In this case, level shifter, which is common collector amplifier, shifts the level by 0.7V. If this shift is not sufficient, the output may be taken at the junction of two resistors in the emitter leg.
- Fig. below shows a complete op-amp circuit having input different amplifiers with balanced output, intermediate stage with unbalanced output, level shifter and an output amplifier.

1.8.4 Internal circuit :- Fig 1



1.8.5 Op-Amp Symbol



Positive power supply

Inverting input terminal
(V2)

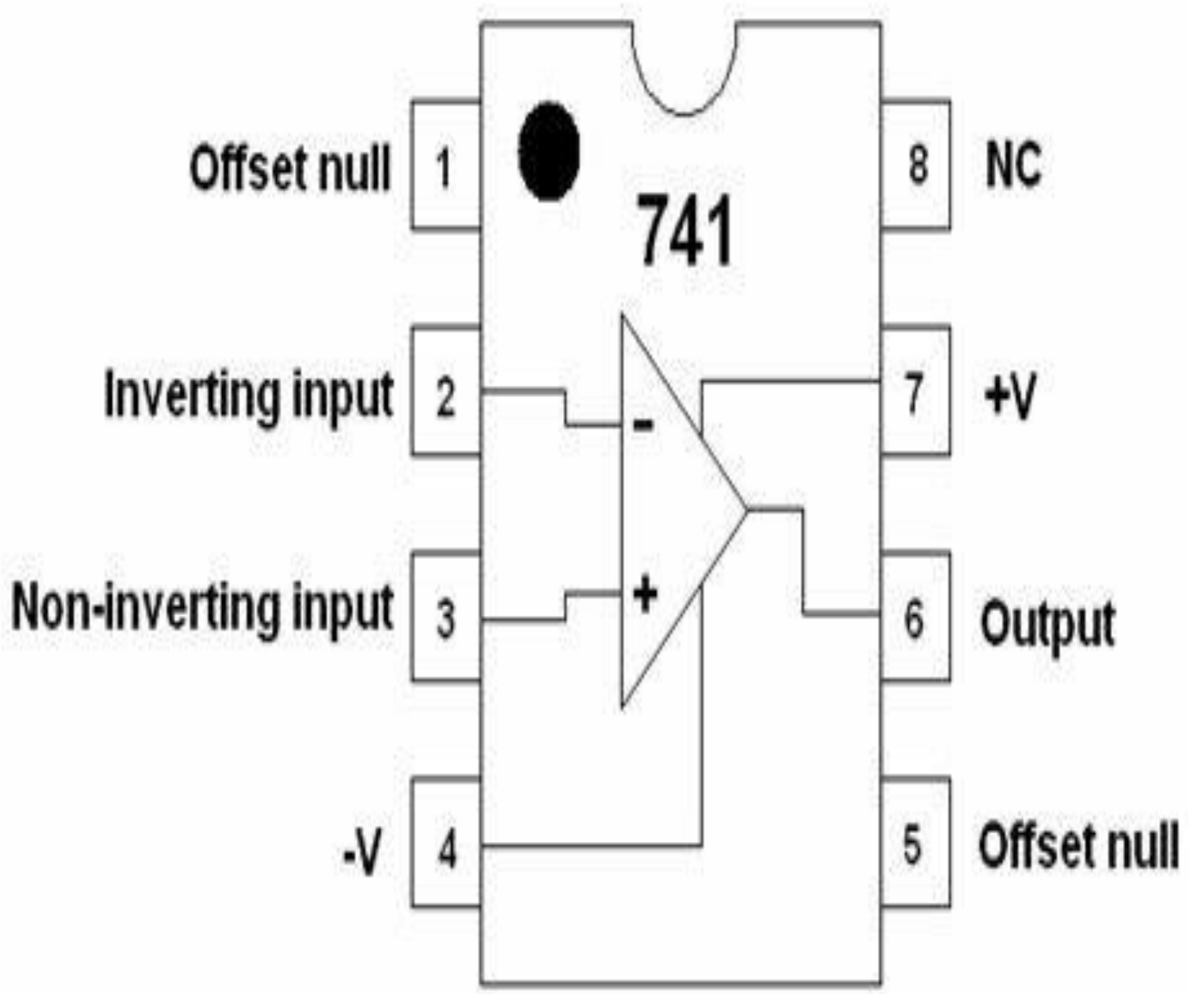
Output terminal

Non-Inverting input terminal
(V1)

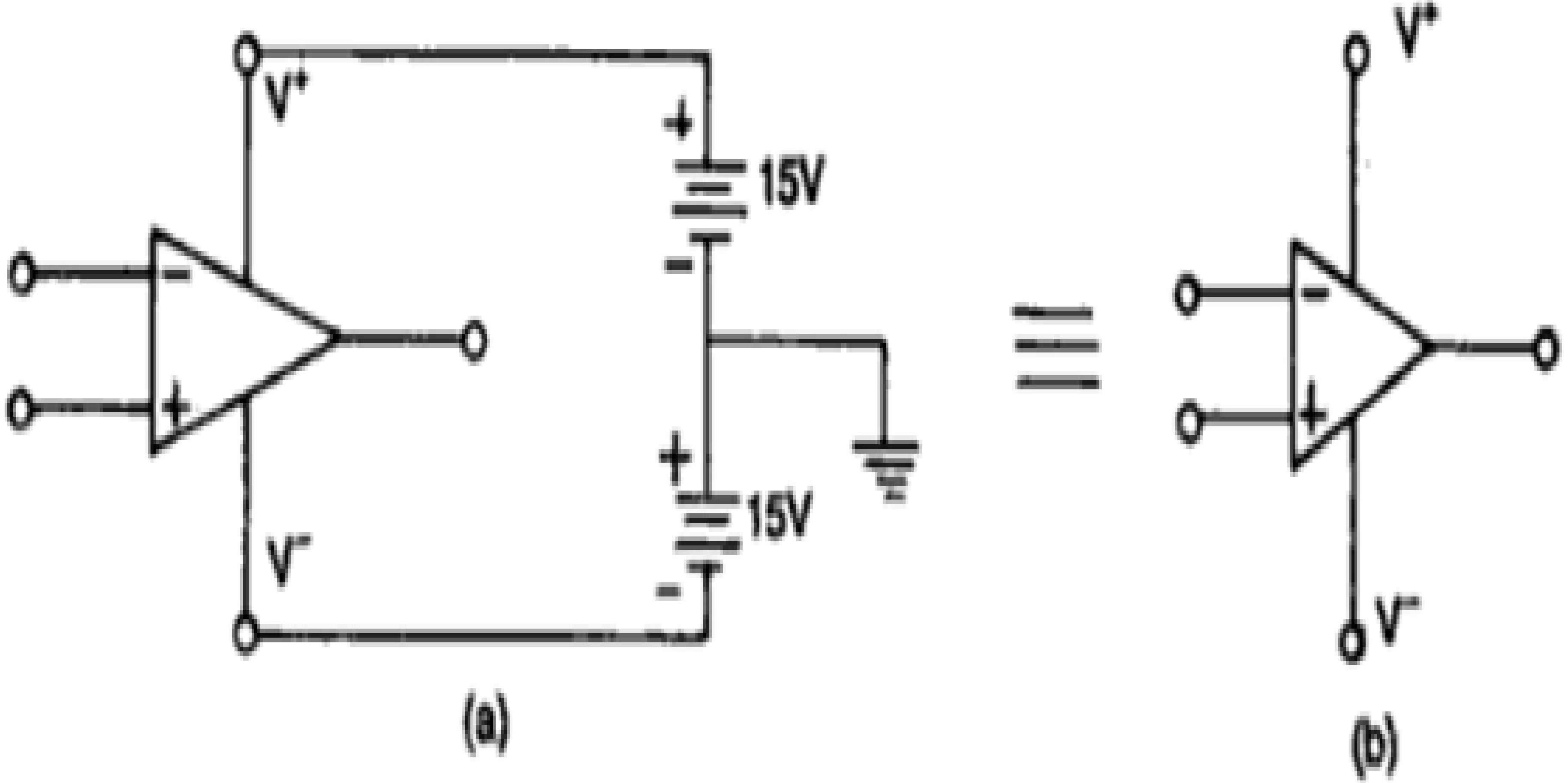
Negative power supply

- Op-amps have five basic terminals, that is, two input terminals, one output terminal and two power supply terminals.
- The power supply voltage may range from about ± 5V to ± 22V. The common terminal of the V+ and V- sources is connected to a reference point or ground.
- The output goes positive when the Non- inverting input (+) goes more positive than the Inverting (-) input, and vice versa.

Pin Diagram : IC µA741C/ LM351



Power Supply Connection of IC µA741C/ LM351



1.8.6 Ideal Characteristics of an OP-AMP Que :- What would be the Characteristics of op-amp as a Amplifier.

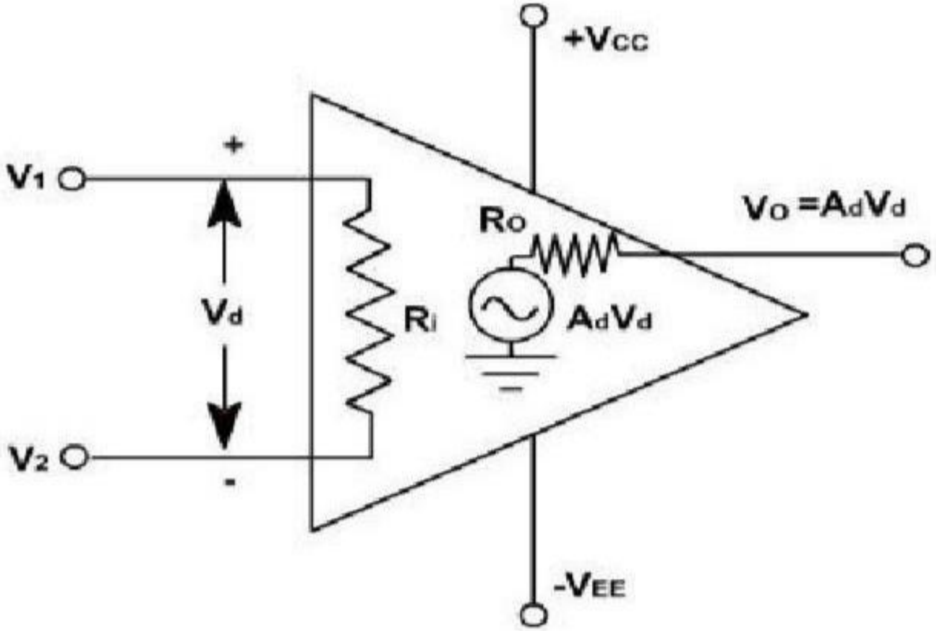
1. Infinite voltage gain.	**$Aol=Ad=A=\infty$**
2. Infinite input resistance so that almost any signal source can drive it and there is no loading on the preceding stage	**$Ri=\infty$**
3. Zero output resistance Ro so that output can drive an infinite number of other devices.	**$Ro=0\ \Omega$**
4. Zero output voltage when input voltage is zero.	**$Vo=0v$ when $V1=V2=0V$**
5. Infinite bandwidth so that any frequency signal from 0 to ∞ Hz can be amplified without attenuation.	**$BW=\infty$**
6. Infinite common mode rejection ratio so that the output common-mode noise voltage is zero.	**$CMRR(p)=\infty$**
7. Infinite slew rate so that output voltage changes occur simultaneously with input voltage changes.	**$SR=\infty$**

1. An ideal op-amp draws no current at both the input terminals i.e. I1 = I2 = 0. Thus its input impedance is infinite. Any source can drive it and there is no loading on the driver stage
2. The gain of an ideal op-amp is infinite, hence the differential input Vd = V1 – V2 is essentially zero for the finite output voltage Vo
3. The output voltage Vo is independent of the current drawn from the output terminals. Thus its output impedance is zero and hence output can drive an infinite number of other circuits

(In Other Words)

1. Open loop gain infinite
2. Input impedance infinite
3. Output impedance zero
4. Bandwidth infinite
5. Zero offset i.e, Vo=0 when V1=V2=0
6. Infinite CMRR
7. Infinite Slew Rate

.8.7 Equivalent circuit of an op-amp/ Low Frequency Model of Op-Amp



$V_o = A_d (V_1 - V_2)$

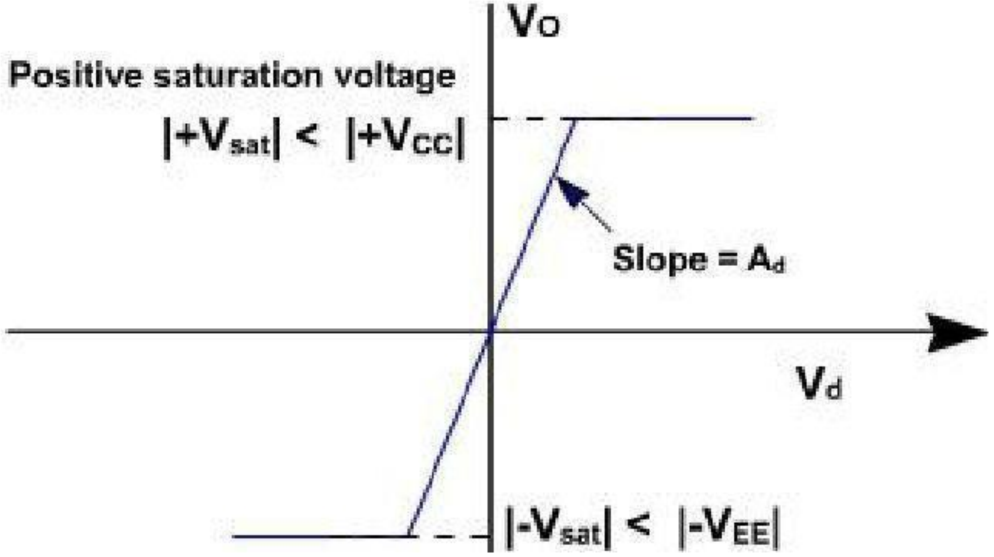
- V1 and V2 are the two input voltages.
- Ri is the input impedance of OPAMP.
- Ad Vd is an equivalent Thevenin's voltage source and
- Ro is the Thevenin's equivalent impedance looking back into output terminal of op-amp.

:- This equivalent circuit is useful in analysing the basic operating principles of op-amp and in observing the effects of standard feedback arrangements.

$$VO = Ad\,(V1-V2) = Ad*Vd.$$

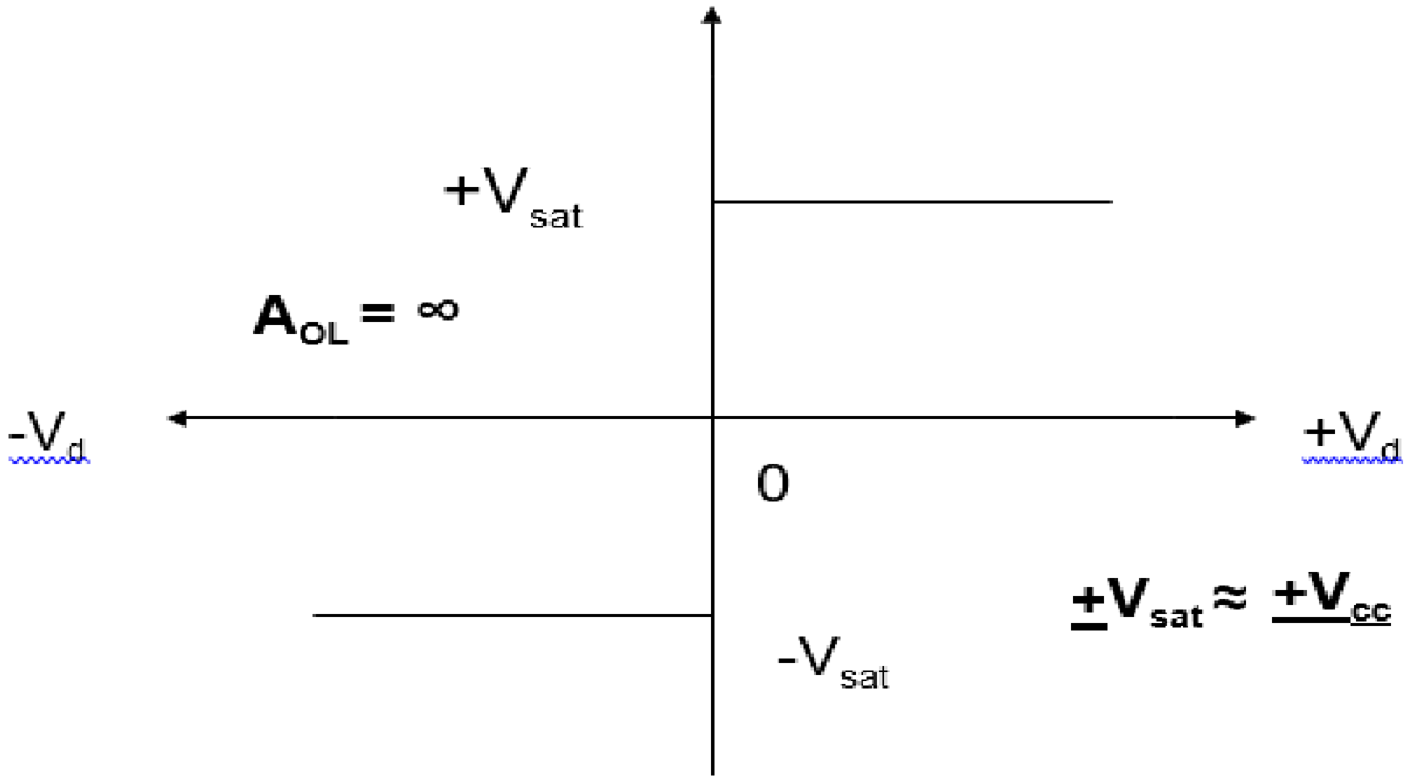
- This equation indicates that the output voltage Vo is directly proportional to the algebraic difference between the two input voltages.
- In other words the opamp amplifies the difference between the two input voltages. It does not amplify the input voltages themselves. The polarity of the output voltage depends on the polarity of the difference voltage Vd.

1.8.8 Practical Voltage Transfer Curve:



- The graphic representation of the output equation is shown in fig.1.2 in which the output voltage Vo is plotted against differential input voltage Vd, keeping gain Ad constant.
- The output voltage cannot exceed the positive and negative saturation voltages. These saturation voltages are specified for given values of supply voltages.
- This means that the output voltage is directly proportional to the input difference voltage only until it reaches the saturation voltages and thereafter the output voltage remains constant. Thus curve is called an ideal voltage transfer curve, ideal because output offset voltage is assumed to be zero. If the curve is drawn to scale, the curve would be almost vertical because of very large values of Ad.

Ideal Voltage transfer curve



1. If Vd is greater than corresponding to b, the output attains +Vsat
2. If Vd is less than corresponding to a, the output attains –Vsat
3. Thus range a-b is input range for which output varies linearily

with the input. But AoL is very high, practically this range is very small

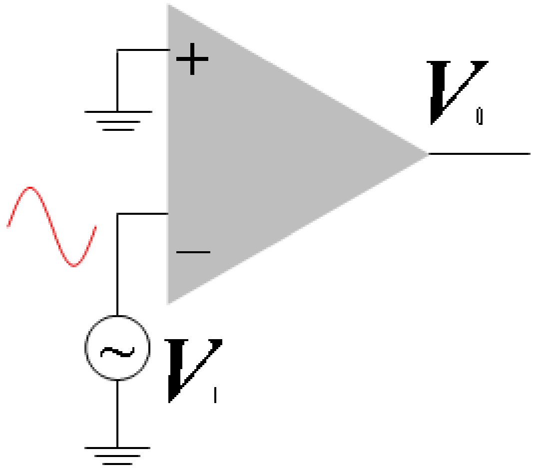
1.8.9 Modes of Operation of op-amp

1. Basic op-amp Configuration/Open Loop Config.

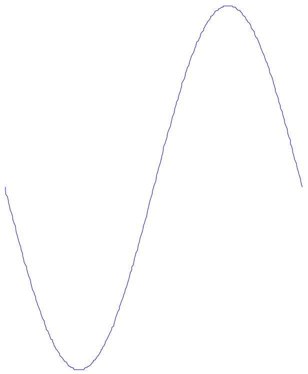
2. Closed loop configuration

1.Open Loop Config.

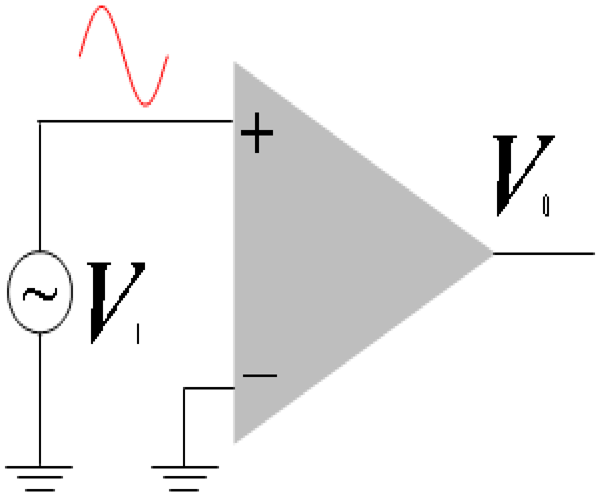
1a) Inverting op-Amp



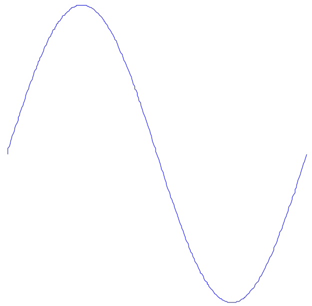
- \+ terminal : Ground
- – terminal : Source
- 180^o phase change



1b) Non-Inverting op-Amp



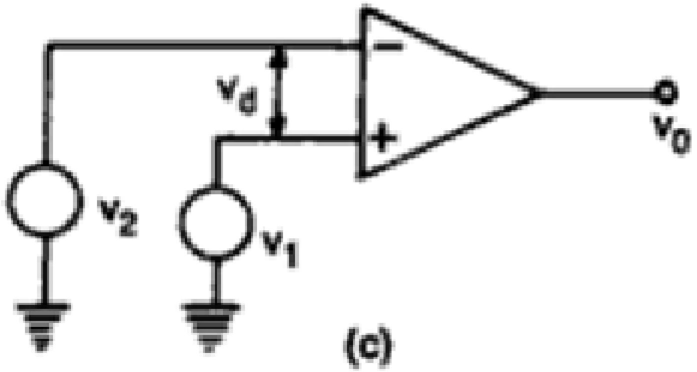
- \+ terminal : Source
- – terminal : Ground
- 0^o phase change



1c. Differential Amplifer

V2 =Vin2

V1 = Vin1

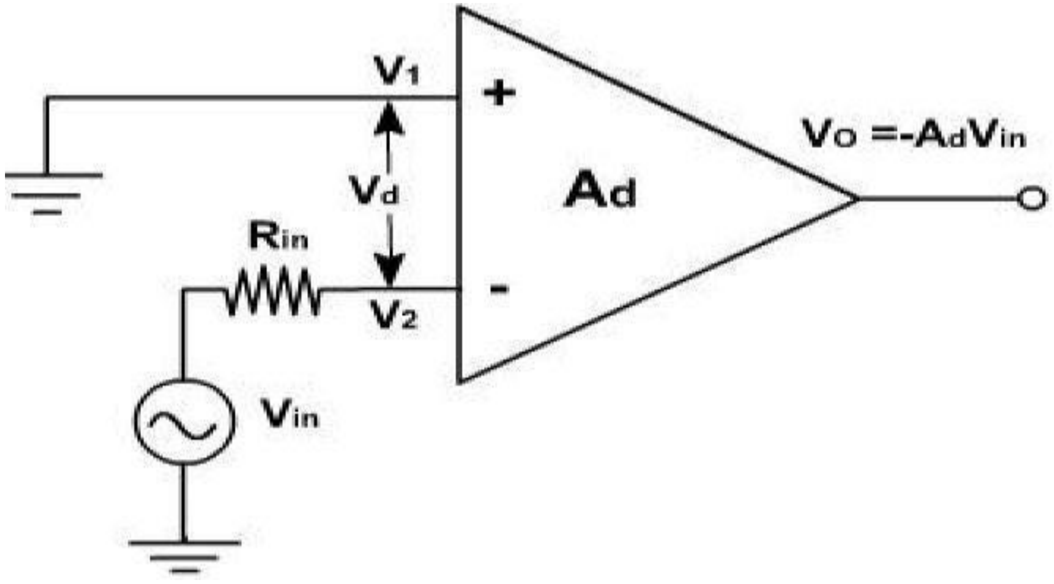


Vo = Ad (vin1- vin2)

- The open loop differential amplifier in which input signals vin1 and vin2 are applied to the positive and negative input terminals.
- Since the OPAMP amplifies the difference the between the two input signals, this configuration is called the differential amplifier.
- The OPAMP amplifies both ac and dc input signals.
- The source resistance Rin1 and Rin2 are normally negligible compared to the input resistance Ri. Therefore voltage drop across these resistances can be assumed to be zero.
- Therefore **V1 = Vin1 and V2 =Vvin2. Vo = Ad (Vin1- Vin2)**
- **where, Ad = Aol = is the open loop gain.**

1a: Open-Loop-Inverting Amplifier : Mathematical Analysis

- If the input is applied to only inverting terminal and non-inverting terminal is grounded then it is called inverting amplifier. This configuration is shown in fig .



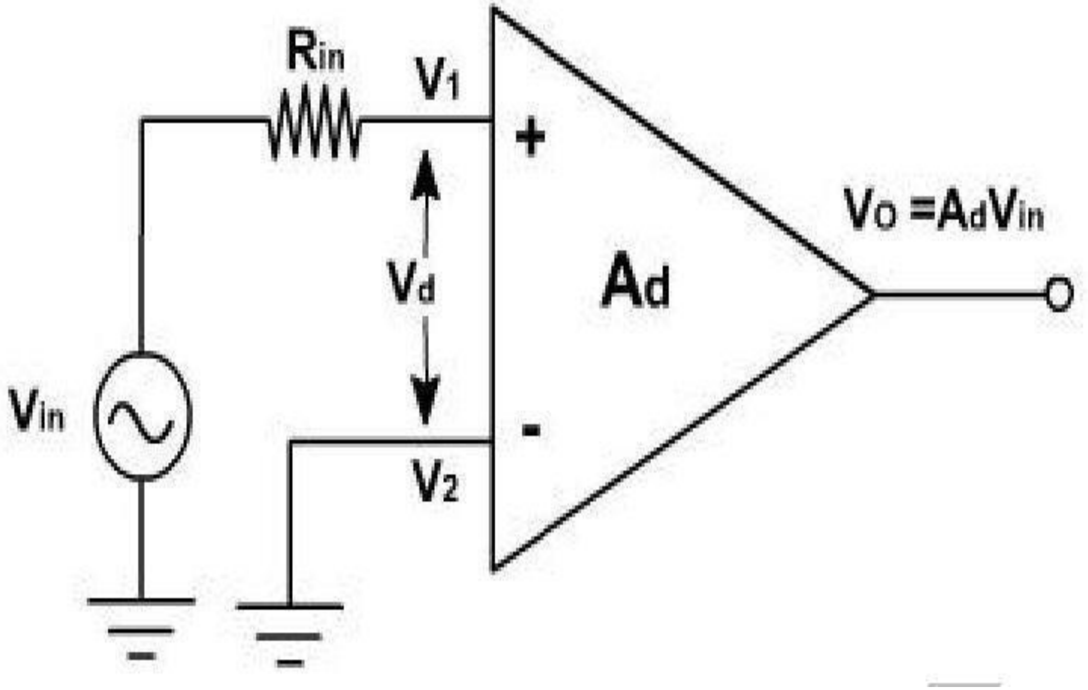
$v1 = 0, \quad v2 = vin.$

$vo = -Ad\, vi$

•The negative sign indicates that the output voltage is out of phase with respect to input 180 ° or is of opposite polarity. Thus the input signal is amplified and inverted also.

1b: Open-loop-Non-Inverting Amplifier

- In this configuration, the input voltage is applied to non-inverting terminals and inverting terminal is ground as shown in fig.
- **v1 = +vin , v2 = 0**
- **vo = +Ad vin**
- **This means that the input voltage is amplified by Ad and there is no phase reversal at the output.**



Applications of Open Loop Configuration i.e. without using any feedback

- The op amp is being used as a voltage comparator. Note that a device designed primarily as a comparator may be better if, for instance, speed is important or a wide range of input voltages may be found, since such devices can quickly recover from full on or full off ("saturated") states.
- A **voltage level detector** can be obtained if a reference voltage V_{ref} is applied to one of the input of op amp. This means that the op amp is set up as a comparator to detect a positive voltage. If the voltage to be sensed, V_i , is applied to op amp's (+) input, the result is a noninverting positive-level detector : when V_i is above V_{ref}, V_O equals $+V_{sat}$; when V_i is below V_{ref}, V_O equals $-V_{sat}$. If V_i is applied to the inverting input, the circuit is an inverting positive-level detector : When V_i is above V_{ref}, V_O equals $-V_{sat}$.
- A **zero voltage level detector** (Vref = 0) can convert, the sine-wave from a function generator into a variable-frequency square wave. If V_i is a sine wave, triangular wave, or wave of any other shape that is symmetrical around zero, the zero-crossing detector's output will be square.

Que. Why op-amp is generally not used in open loop mode ?

Ans :-

- **As open loop gain of op-amp is very large, very small input voltage drives the op-amp voltage to the saturation level.**
- **Thus in open loop configuration, the output is at its positive saturation voltage (+Vsat) or negative saturation voltage (-Vsat) depending on which input V1 or V2 is more than the other. For a.c. input voltages, output may switch between positive and negative saturation voltages.**

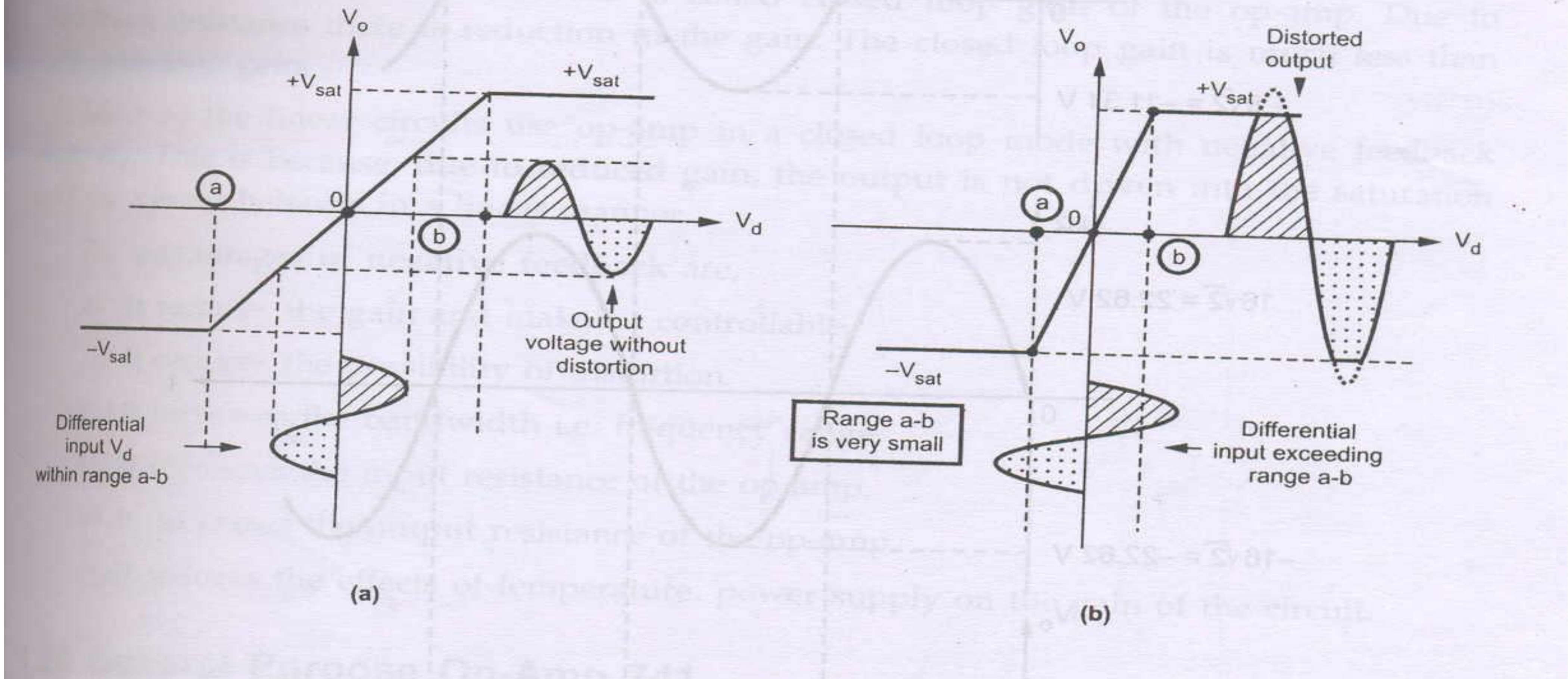


Fig. 1.55

- **This indicates the inability of op-amp to work as a linear small signal amplifier in the open loop mode. Hence the op-amp in open loop configuration is not used for the linear applications**

1.8.10 Characteristics or performance parameters of Op-amp
A) DC Characteristics

- **Input bias current**
- **Input offset current**
- **Input offset Voltage**
- **Thermal Drift**

B) AC Characteristics

- Differential input resistance
- Input capacitance
- Open loop voltage gain/ Large Signal Voltage gain
- CMRR
- Output voltage swing Output resistance
- Offset adjustment range
- Input Voltage range
- Power supply rejection ratio
- Power consumption
- Slew rate
- Gain – Bandwidth product
- Equivalent input noise voltage and current

1. Input Bias Current : Ib

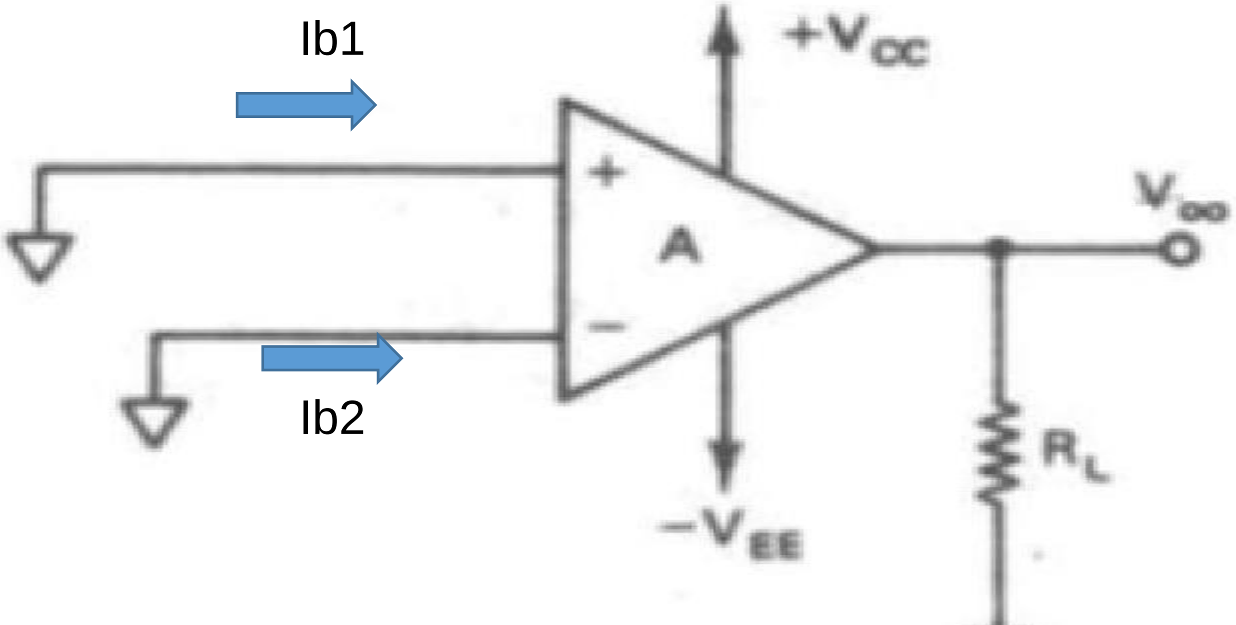
- The input bias current IB is the average of the current entering the input terminals of a balanced amplifier as shown in fig. i.e.

$$Ib = (Ib1 + Ib2)/2$$

Ib1= dc bias current flowing into the Non-inverting input

Ib2= dc bias current flowing into the Inverting input

- The input bias currents Ib1 and Ib2 are the Base bias currents of the two transistors in the (First) differential amplifier stage of the op-amp.



- Even though both of the input transistors are identical, it is not possible to have Ib1 and Ib2 exactly equal to each other because of the internal imbalance between the two inputs.
- In this section we use the specified input bias current Ib as being equal to either one of the two input currents Ib1 or Ib2; that is

$$Ib = Ib1 = Ib2$$

- For ideal op-amp Ib=0.
- **But Practically 741C Ib(max) = 700 nA**
- **and for precision 741C IB = ± 7 nA**

2. Input offset Current: Iio

- The difference between the bias currents at the input terminals of the op- amp is called as input offset current.
- The input terminals conduct a small value of dc current to bias the input transistors.
- Since the input transistors cannot be made identical, there exists a difference in bias currents.
- This is called input offset current Iio.
- The input offset current Iio is the difference between the currents into inverting and non-inverting terminals of a balanced amplifier as shown in fig.

$$Iio = | Ib1 - Ib2 |$$

- **The Iio for the 741C is 200nA maximum.**
  If the matching between two input terminals is improved, the difference between IB1 and IB2 becomes smaller, i.e. the Iio value further decreases.

For a precision OPAMP 741C, Iio is 6 nA

3. Thermal Drift :

Bias current, offset current and offset voltage changes with temperature. A circuit nulled at 25^0C may not remain constant, when the temperature rises to 35^0 C. This is called Drift.

4. Input offset voltage: Vio

- If no external input signal is applied to the op-amp at the inverting and non-inverting terminals the output must be zero. That is, if Vi=0, Vo=0.
- But as a result of the given biasing supply voltages, +Vcc and **–**Vcc, a finite bias current is drawn by the op-amps, and as a result of asymmetry on the differential amplifier configuration, the output will not be zero. This is known as offset (Output Offest Voltage).
- Input offset voltage Vio is the differential input voltage that exists between two input terminals of an op-amp without any external inputs applied.
- In other words, it is the amount of the input voltage that should be applied between two input terminals in order to force the output voltage to zero.
- Let us denote the output offset voltage due to input offset voltage Vio as Voo. The output offset voltage Voo is caused by mismatching between two input terminals.

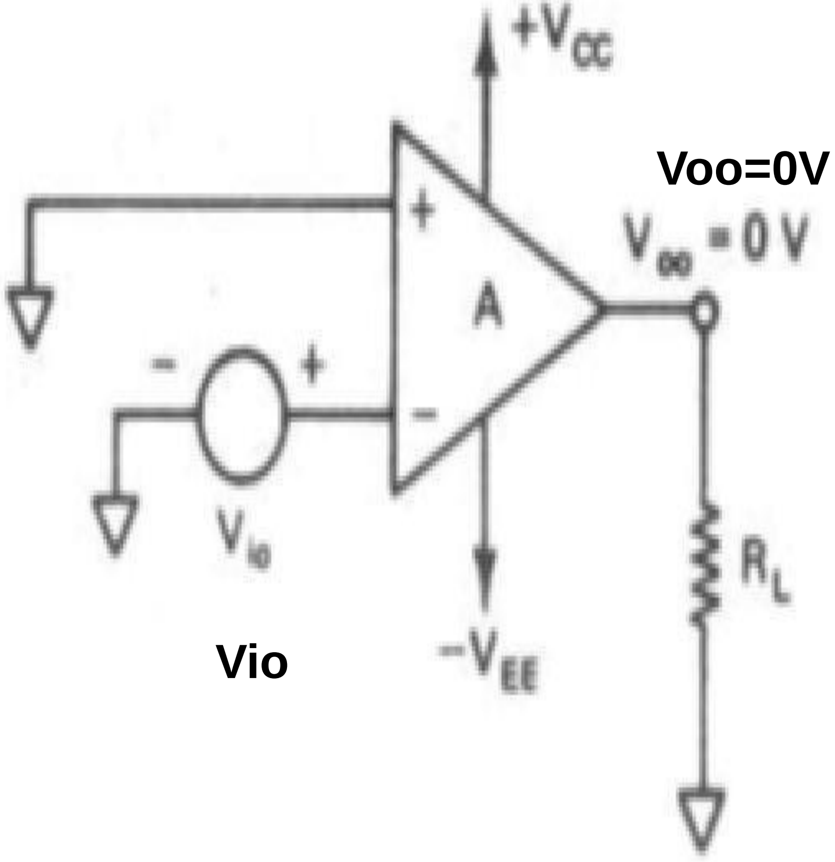


Fig1.Input offset voltage in an op-amp

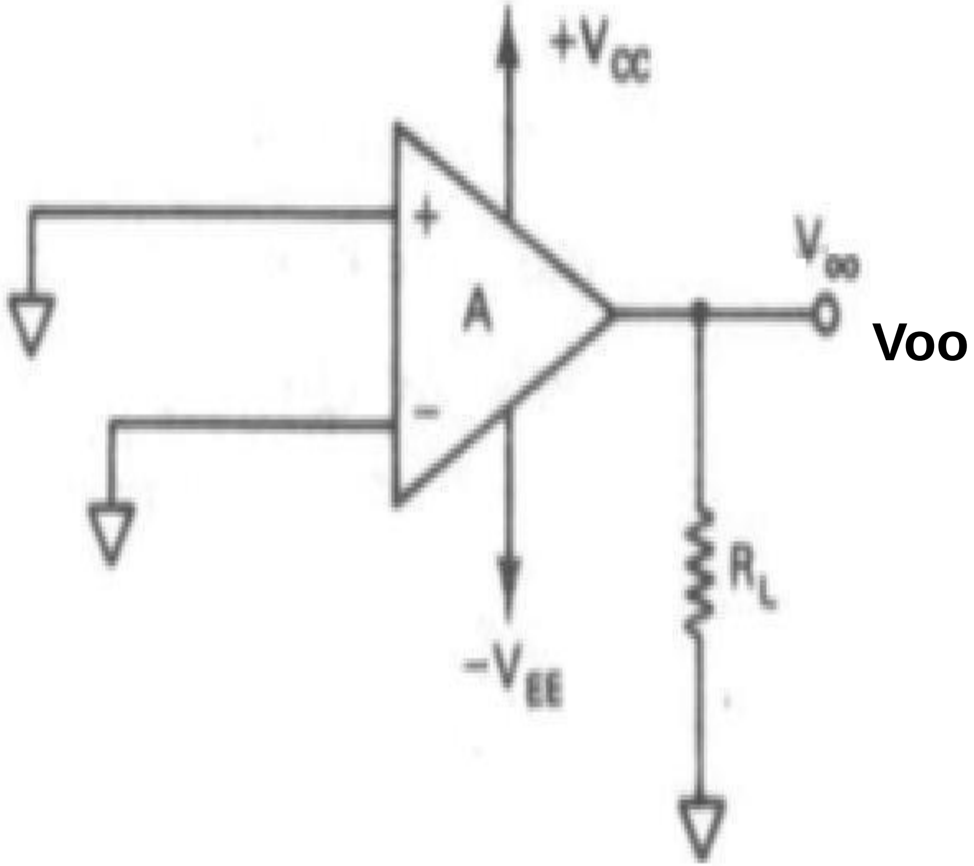


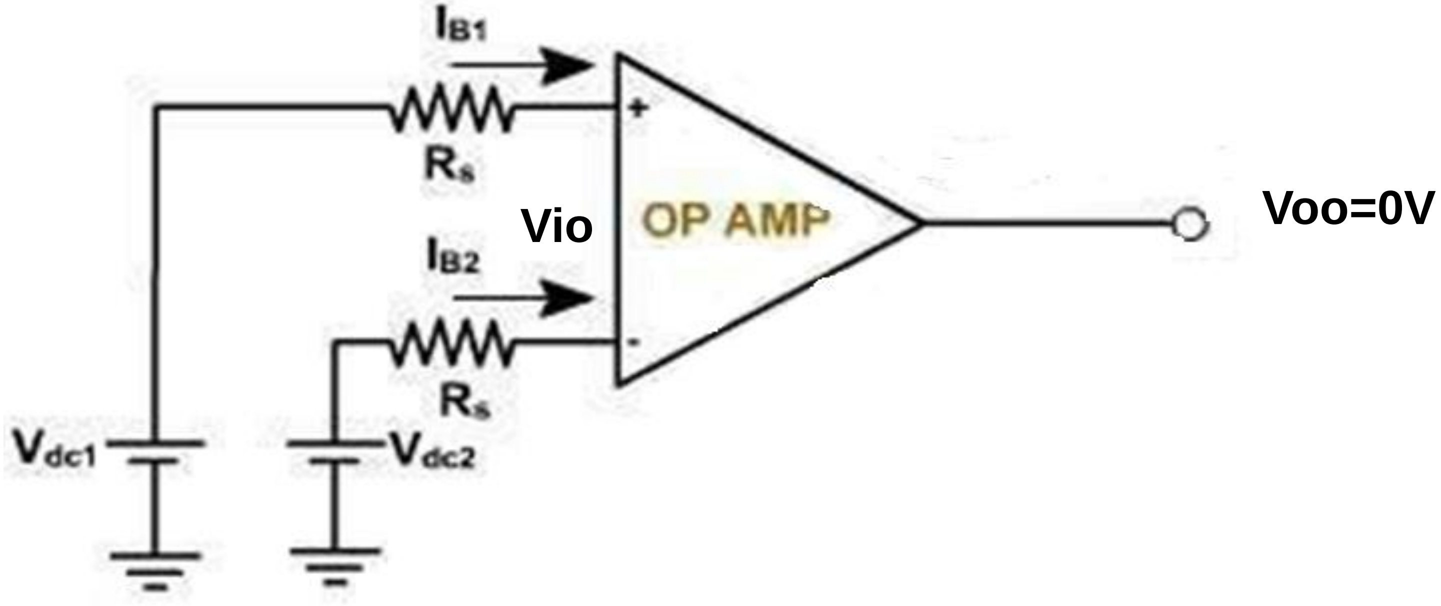
Fig 2.Output offset voltage in op-amp

- **For a 741 C the maximum value of Vio is 6mV dc. Smaller the value of Vio, better the input terminals are matched.**

  for eg. The 741 precision op amp has Vio= 150 µV max.

- Since Vo must be zero when Vin=0 , an input voltage must be applied such that the output offset is cancelled and Vo is made zero.
  This is known as input offset voltage.
- Input offset voltage (Vio) is defined as the voltage that must be applied between the two input terminals of an OPAMP to null or zero the output voltage. Fig. shows that two dc voltages are applied to input terminals to make the output zero.

Vio = Vdc1- Vdc2

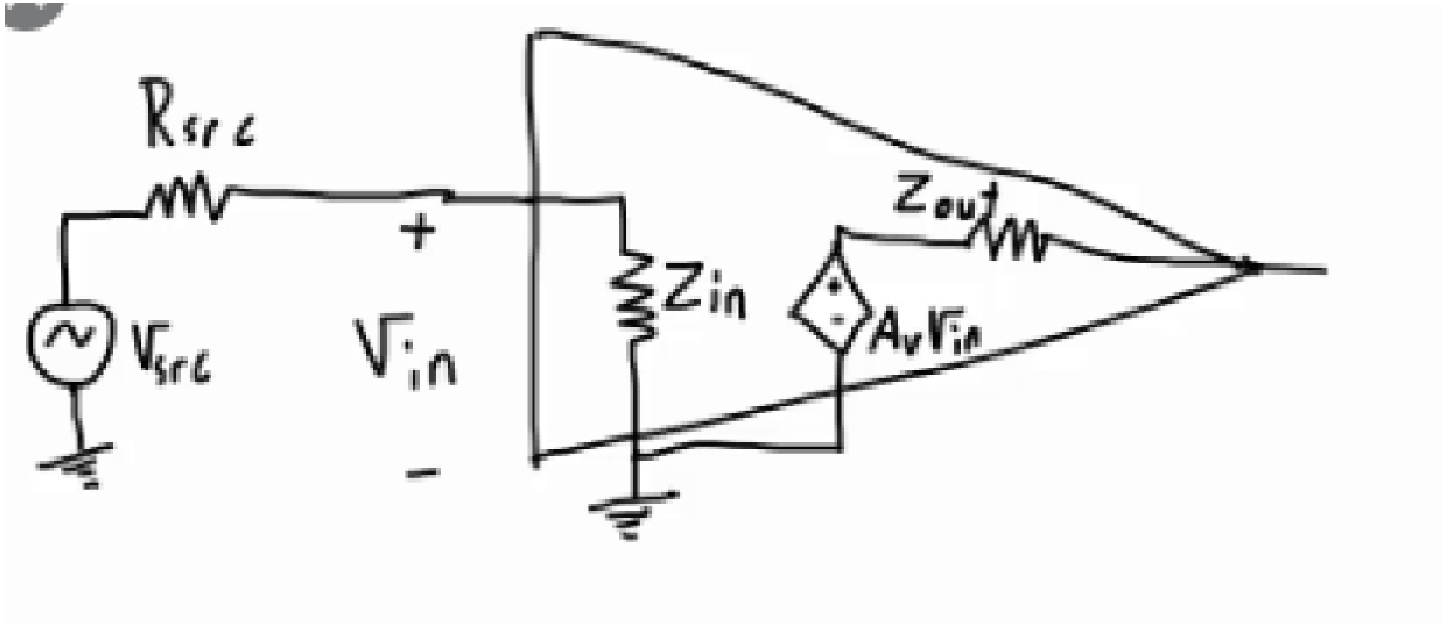


B) AC Characteristics

5. Differential Input Resistance: (Ri)

Ri is the equivalent resistance that can be measured at either the Inverting or Non-inverting input terminal with the other terminal grounded.

For the 741C the input resistance is relatively high 2 MΩ.
For some OP-AMP it may be up to 1000 G ohm.



6. Input Capacitance: (Ci)

Ci is the equivalent capacitance that can be measured at either the inverting and non inverting terminal with the other terminal connected to ground.

A typical value of Ci is 1.4 pf for the 741C.

7. Open loop voltage gain / Large Signal Voltage Gain :

(Ad = Adm = AoL = A = $2*10^5$)

Since the OPAMP amplifies difference voltage between two input terminals, the voltage gain of the amplifier is defined as

$$\text{Voltage gain} = \frac{\text{Output voltage}}{\text{Differential input voltage}}$$

$$A = \frac{V_0}{V_{id}}$$

- **It is the ratio of output voltage to the Differential input voltage, when op-amp is in open loop configuration , without any feedback is called the Large Signal voltage gain**
- Because output signal amplitude is much large than the input signal the voltage gain is commonly called large signal voltage gain.
- **For 741C voltage gain is 2,00,000 ie. $2*10^5$ typically.**

8. Common Mode Rejection Ratio (CMRR).

- CMRR is defined as the ratio of the differential voltage gain Ad to the common mode voltage gain Acm. ie,

CMRR = Ad / Acm.

- **Ad is same as the large-signal voltage gain A, which is equal to $2*10^5$**
- **Common mode voltage gain can be determined from the ckt of fig.using the eq.**

Acm=Vocm/ Vcm

where, Vocm = Common mode voltage gain

Vcm = Common mode voltage gain

Acm = Common mode voltage gain

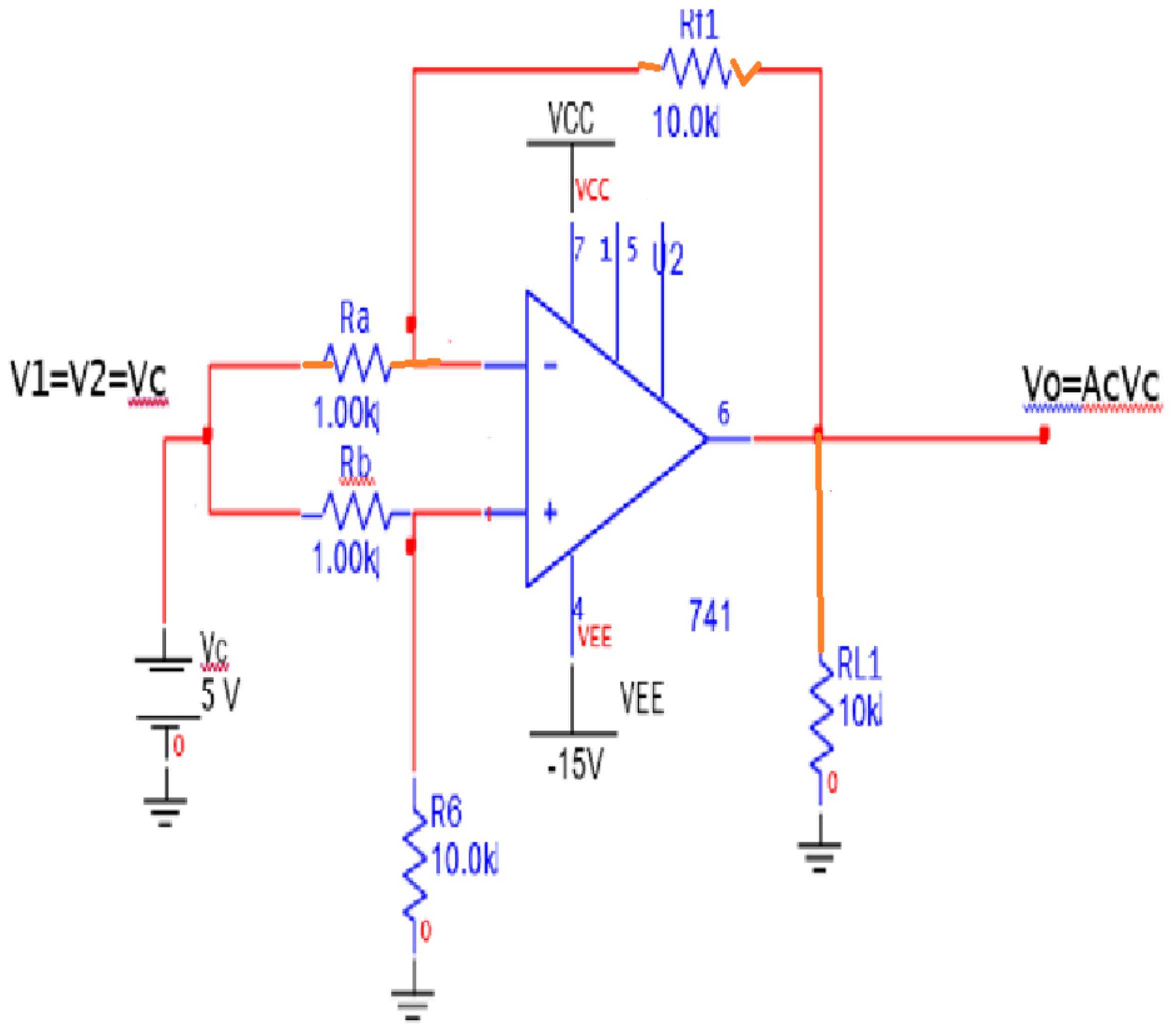
- **For the 741C, CMRR is 90 dB typically.**
- **The higher the value of CMRR the better is the matching between two input terminals and the smaller is the output common mode voltage.**

- How To Calculate CMRR for IC -741 :

  - For differential mode apply V1 = 2V, V2 =1V. Measure the o/p voltage Vo.
  - Calculate Adm = Vo /V1-V2, which comes out to be nearly = $2*\mathbf{10^5}$
  - For common mode, V1 = V2 = 1V. Measure the output Voltage Vo. Which is very very low (uV). Ideally 0V
  - Calculate Acm = Vo / V1.
  - Find CMRR = Adm/ Acm = Very very high value, so that coverted into Decibel.
  - CMRR in dB = 20 log10 (CMRR). 170 dB

- Find CMRR= Ad/Acm which is a integer value , very very High in thousands
- Since it is a High Value, It is converted into Decibel

- **i.e. CMRR in Decibel (dB) = 20 log $_{20}$ (Aol/ Acm) ---Very imp relation**



=0.005 V = in uV

OP-AMP connected in common mode configuration

9. Output voltage Swing:

- The ac output compliance PP is the maximum unclipped peak to peak output voltage that an OPAMP can produce.
- Since the quiescent output is ideally zero, the ac output voltage can swing positive or negative. This also indicates the values of positive and negative saturation voltages of the OP-AMP.
- **The output voltage never exceeds these limits for a given supply voltages +VCC and -VEE.**
- **For a 741C it is ± 13 V.**

10. Output Resistance: (RO)

- RO is the equivalent resistance that can be measured between the output terminal of the OPAMP and the ground.
- **It is 75 ohm for the 741C OPAMP.**

11. Offset Voltage Adjustment Range:

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 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 741C the offset voltage adjustment range is ± 15 mV.

12. Output Short circuit Current :

In some applications, an OPAMP may drive a load resistance that is approximately zero. Even its output impedance is 75 ohm but cannot supply large currents. Since OPAMP is low power device and so its output current is limited. The 741C can supply a maximum short circuit output current of only 25mA.

13. Supply Current:

IS is the current drawn by the OP-AMP from the supply. For the 741C OPAMP the supply current is 2.8 m A.

14. Power Consumption:

Power consumption (PC) is the amount of quiescent power (Vin= 0V) that must be consumed by the OPAMP in order to operate properly. The amount of power consumed by the 741C is 85 m W.

Need for frequency compensation in practical op-amps:

Frequency compensation is needed when large bandwidth and lower closed loop gain is desired. Compensating networks are used to control the phase shift and hence to improve the stability.

Frequency compensation methods: a) Dominant- pole compensation b) Pole- zero compensation.

1.8.11 AC Chacteristics :

15. Slew Rate (SR) is defined as the maximum rate of change of output voltage per unit of time and is expressed in **V/µsec** (caused by a step input voltage).

- An ideal slew rate is infinite which means that op-**amp's output voltage** should change instantaneously in response to input voltage i.e. step voltage.

$$\boxed{\mathbf{SR = dV_o /dt \,|_{max}}}$$

- slew rate indicates how rapidly the output of an op-amp can change in response to changes in the input frequency.
- It is normally specified at **unity (+1) gain** condition.
- Slew rate of an op-amp is fixed : therefore ; if the slope requirements of the output signal are greater than the slew rate, then Distortion occurs.
- **Thus Slew Rate is one of the imp factor in Selecting the op-amp for AC applications, particularly at high freq.**
- **Typical value for 741 op-amp is 0.5 V/µsec or 0.5 * 10^6 V/sec. This is draw back of 741. the newer op-amp µAF-771, LF-351 & MC 34001 are the direct replacement for 741C. have a slew rate of 13 V/µsec. The LM 318 has a slew rate of 70 V/µsec.**

Slew rate equation :

Vs = Vm sinωt , Vo = Vm sinω, S = slew rate = $\frac{dVo}{dt}\Big|_{max}$ = **Vm ω cosωt**

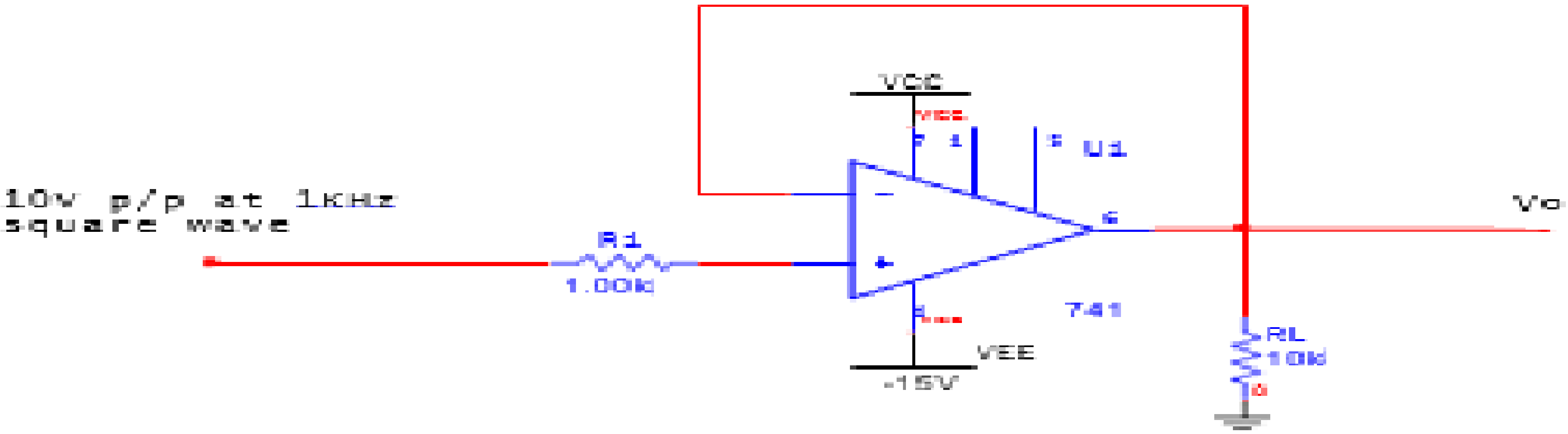
S = Vm ω = 2 π f Vm ---------------------------------- **since, cosωt = +, - 1**

S = 2 π f Vm --------V / sec

For distortion free output, the maximum allowable input frequency fm can be obtained as

$$Fm = \text{maximum frequency} = S / 2\pi \cdot Vm$$ **------in Hz**

This is also called
full power bandwidth
of the op-amp



circuit diagram for calculating slew rate

How to Measure Slew Rate Practically and Theortically :-

a. Practically :

Adjust a square waveform from a signal generator so that, the output is 10 volts peak to peak, at 1 Khz.

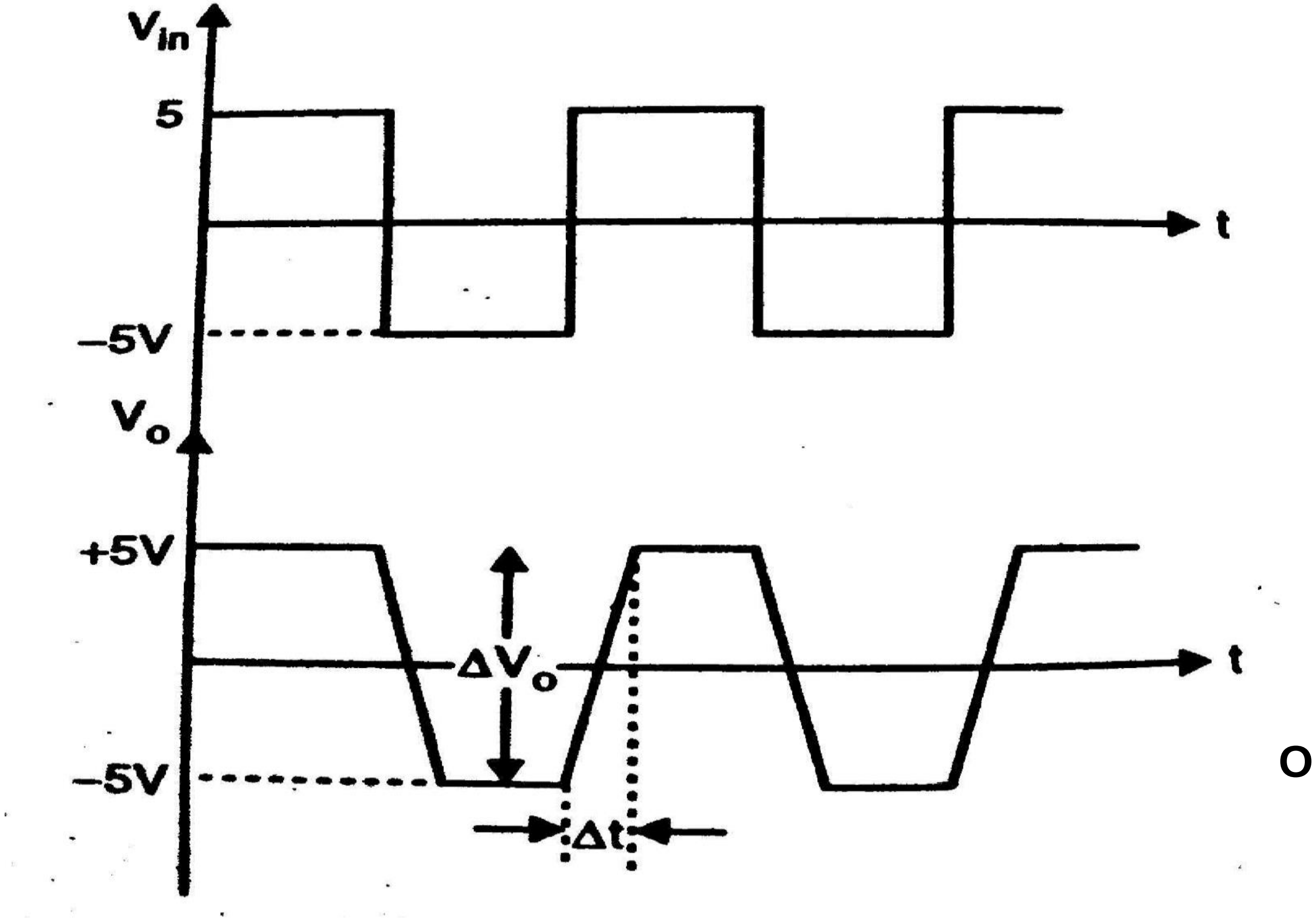
- Increase the i/p frequency slowly until the output is just barely a triangular wave.
- Take 4-5 Readings by Increasing the i/p frequency slowly.
- Find Slew Rate using formula ,

S. R. = $\Delta V_o / \Delta t$ -------- volts/ µsec.

- Calculate Slew Rate using above formula.
- S. R. = $\Delta V_o / \Delta t$ = is nothing but the Slope of the Output wave form.

Where, ΔV_o = Change in output voltage

Δt = Change in time.



Input Waveform

Output Waveform

b. SR Calculation, Theoretically :-

Also, calculate Slew Rate Theoretically using formula given below

Slew Rate = $2 \pi f V_m / 2 * 10^6$ ----- V/μsec ----- using formula

2. Open Loop Gain Vs Freqency Response of op-amp, Gain - Bandwidth Product and Bandwidth with Feedback :

The Bandwidth of an amplifier is defined as the band of Freqencies for which the gain remains constant. Manufacturers generally specify either the Gain - Bandwidth Product Or simply Open Loop Gain Vs Freqency curve for the op-amp

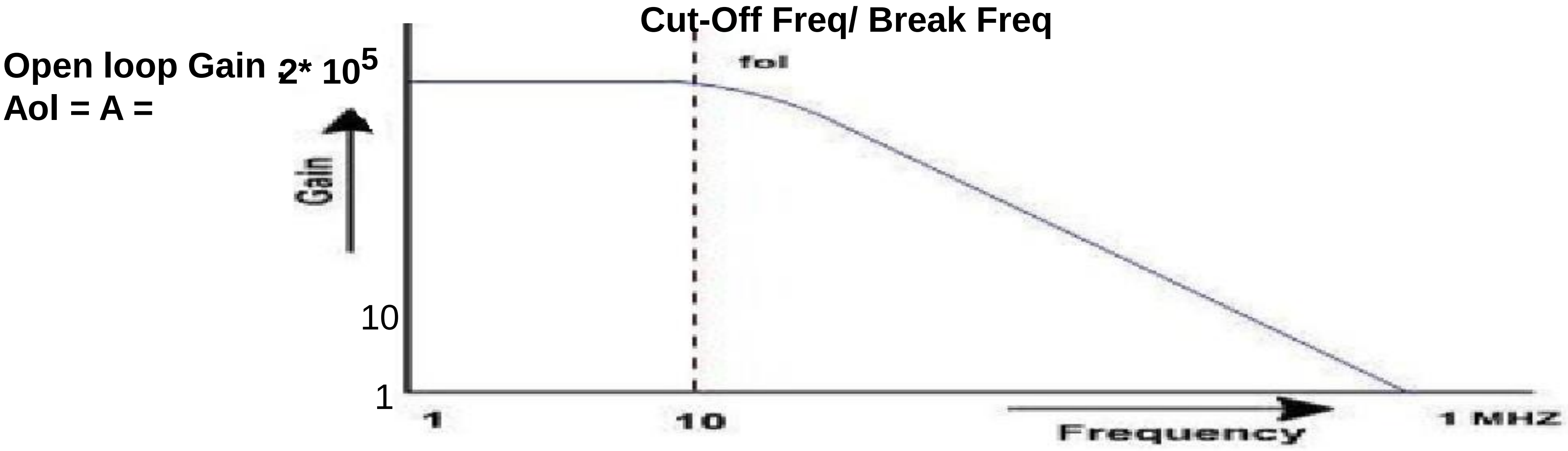
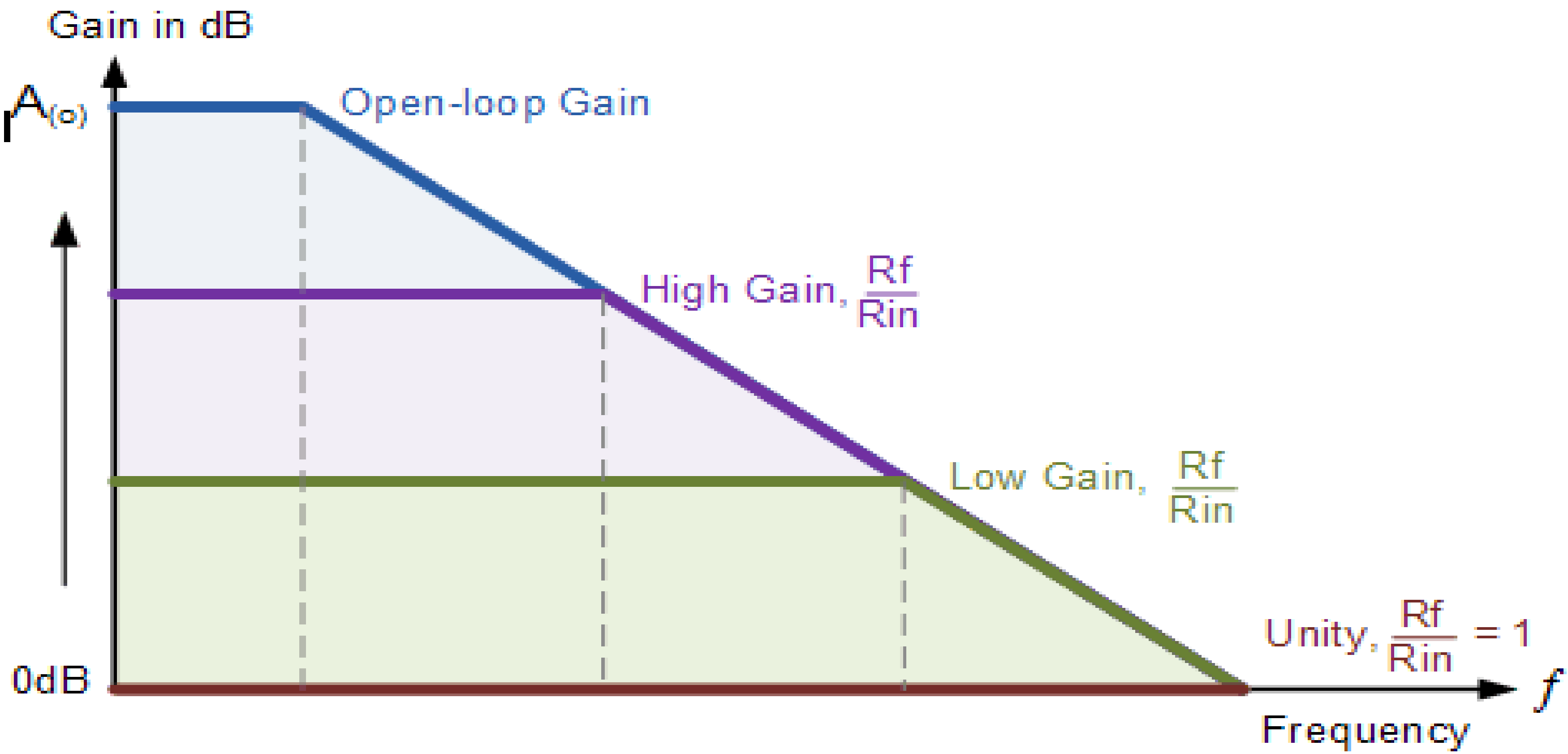


Fig : Open-Loop Gain Versus Freqency Curve of op-amp 741 / Band width of OP-AMP

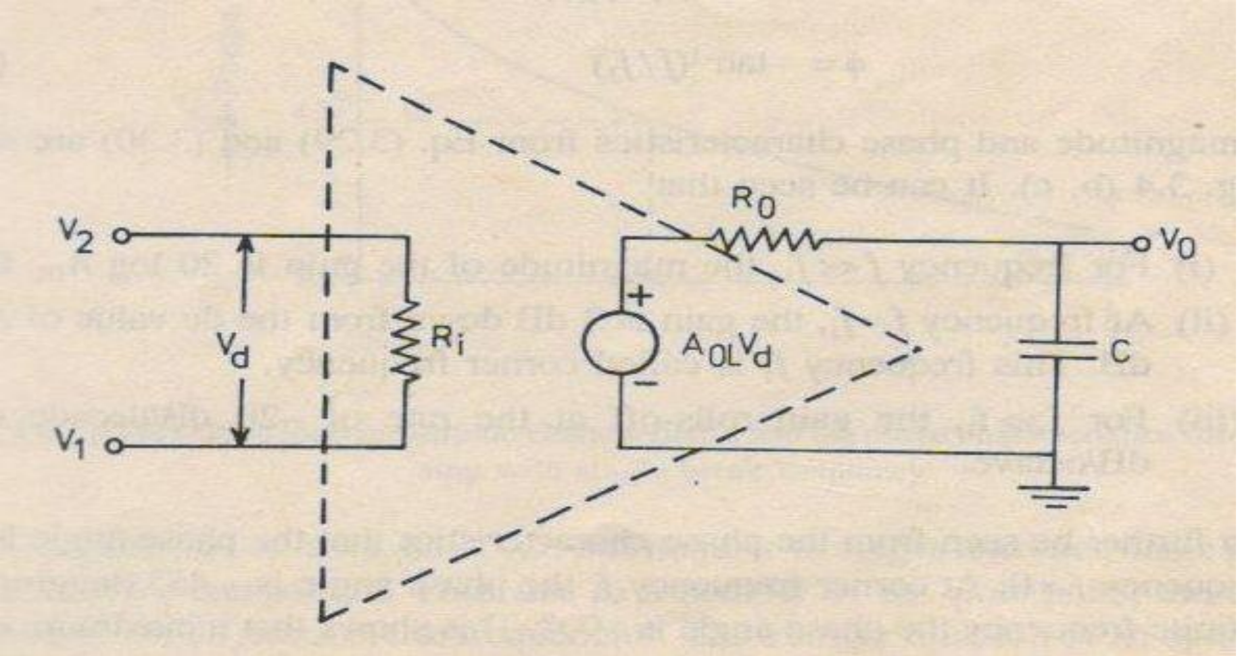
Operational Amplifier Gain

Open Loop Gain=Aol
= A



- The Open-loop gain called the **Gain Bandwidth Product**, or (GBP) can be very high and is a measure of how good an amplifier is.
- Very high GBP makes an operational amplifier circuit unstable as a micro volt input signal causes the output voltage to swing into saturation.
- By the use of a suitable feedback resistor, (Rf) the overall gain of the amplifie can be accurately controlled.

HIGH FREQUENCY MODEL OF OPAMP



The GB is also called unity gain bandwidth (UGB) or closed loop bandwidth. It is about 1MHz for op-amp IC-741C.

- Fig. Shows that the open- loop gain Vs frequency curve of the 741 op-amp.
- From this curve for a gain of $\mathbf{10^5}$, the bandwidth is 10 Hz,
  OR the gain bandwidth product is ($\mathbf{10^5}$ * 10 Hz) = 1 MHz.
- On the other extreme, the bandwidth is approx. 1 MHz when the Gain is 1.
- Thus gain bandwidth product is 1 MHz ie. constant.
- This holds true only for op-amp like 741 that just, have one Break frequency.
- For 741, 10Hz is the Break frequency, the freq at which the gain A is 3 dB down from its Max. value
- On the other hand the frequency at which the gain equals 1 is known as the Unity gain bandwidth (UGB).
- The relationship between the Break frequency fo, open- loop voltage gain (A), bandwidth with Feedback $f_{f,}$ and the Closed – loop gain Af can be written as follows.

- **Since for an op-amp like 741 with a single Break frequency fo, the gain bandwidth product is constant, and is equal to the Unity gain--bandwidth (UGB), we can write,**

UGB = A .fo ------ eq.1

Or alternately . For a single Break freq. op-amp,

UGB= Af. f_f --------eq. 2

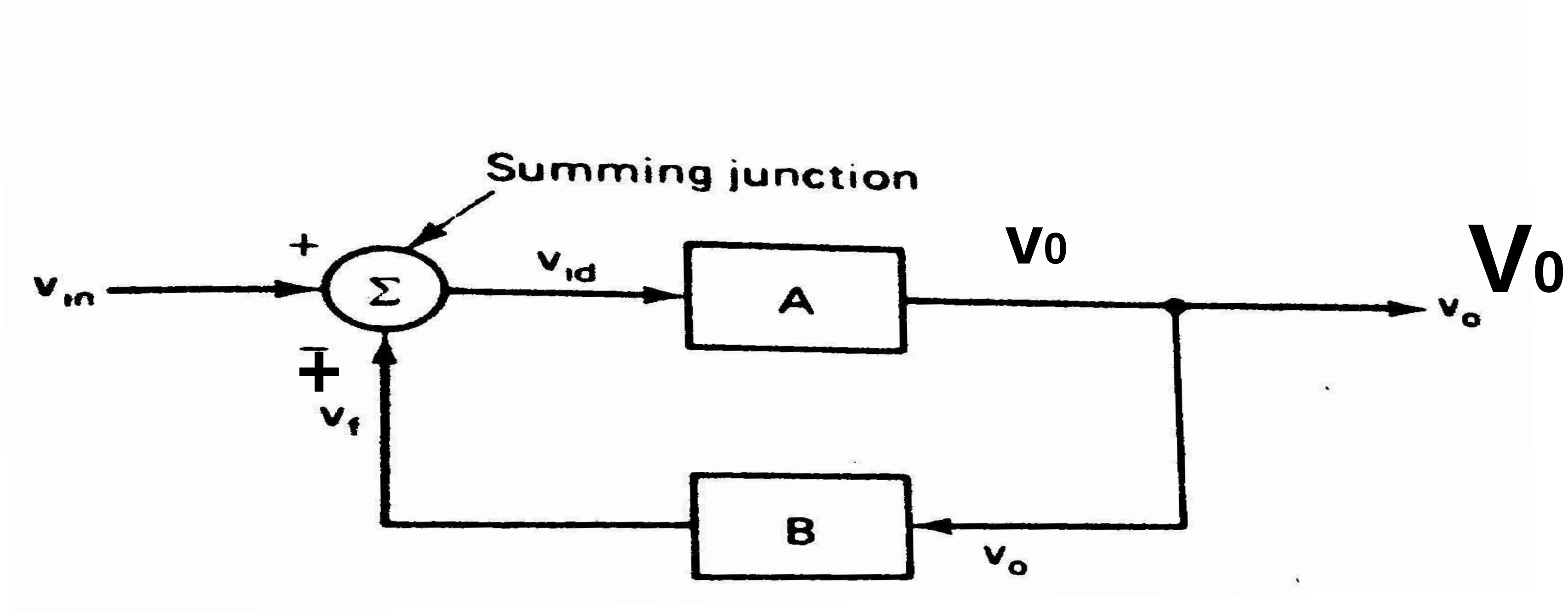
:- Equating above two equations. We can find closed loop gain / bandwidth as given by following equation.

Af = A. fo/ f_f

2. Closed loop configuration

- We can control the gain of the op-amp if we introduce the feedback to the input i.e. an output signal is fed back to the input via feedback network.

a) If the signal fed back is of opposite polarity or out of phase by 180 degree w. r. to the input signal, the feedback is called “Negative Feedback”.



- **Negative Feedback is also known as Degenerative Feedback”,** because When it used, it reduces the output voltage amplitude and in turn reduces the Voltage Gain.

:- **So, before proceeding, it is necessary to Define some important terms. Specially the Voltage gain of the op-amp with and without feedback and the Gain of the feedback circuit are Defined as follows**

- **Open- Loop voltage Gain gain (or Gain without feedback),** $A = v0/vid$
- **Closed -Loop voltage Gain (or Gain with feedback) ,** $Af = Vo/ Vin$
- **Gain of the feedback circuit ,** $B = Vf/Vo$

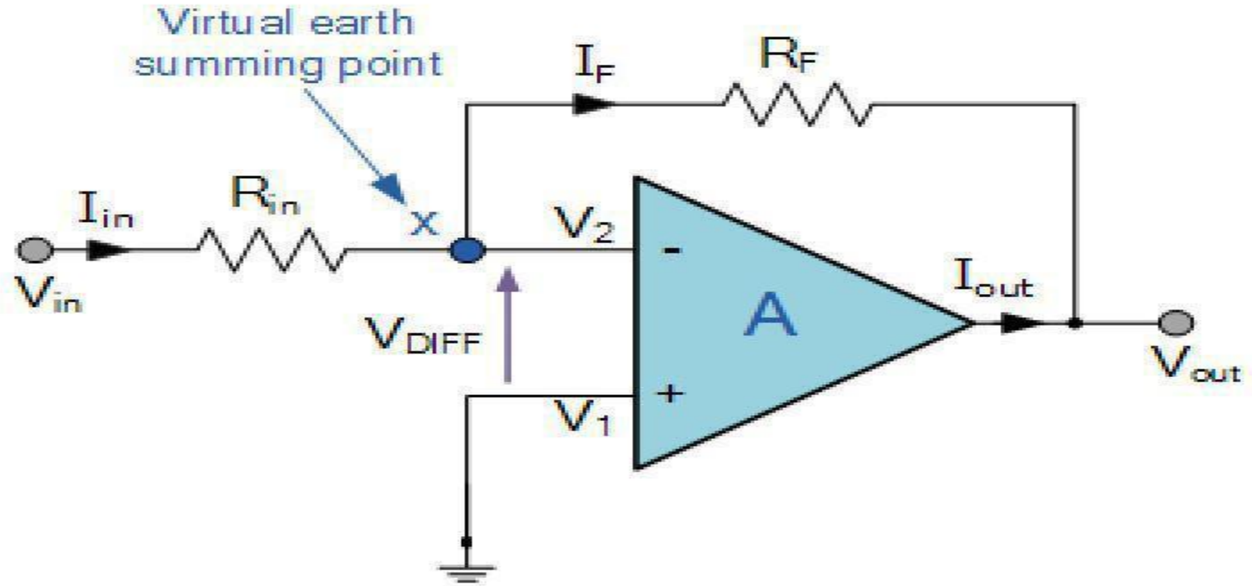
b) **And if the signal fed back is of the same polarity or in phase with the input signal, the feeback Is called “Positive Feedback”.**

In Positive Feedback the feedback signal aids the input signal. therefore it is also refered to as **“Degenerative Feedback”.** Positive Feedback, is necessary in Oscillator Circuits.

Advantages of Negative Feedback :

- **When used in amplifiers, Negative fed back, Stabilizes the Gain.**
- **Increases the Bandwidth.**
- **and changes the input & Output resistances.**

2a. Closed Loop Inverting Amplifier



- In this Inverting Amplifier circuit the operational amplifier is connected with feedback to produce a closed loop operation.
- **For ideal op-amps there are two very important rules to remember about inverting amplifiers:**
- These are: **"no current flows into the input terminal"** and that **“V1 equals V2”.**

- This is because the junction of the input and feedback signal (X) is at the same potential as the positive (+) input which is at zero volts or ground then, the junction is a **“Virtual Earth".**

- We said above that there are two very important rules to remember about Inverting Amplifiers or any operational amplifier for that matter and these are.
- **ASSUMPTIONS are Ri & A are Infinity**

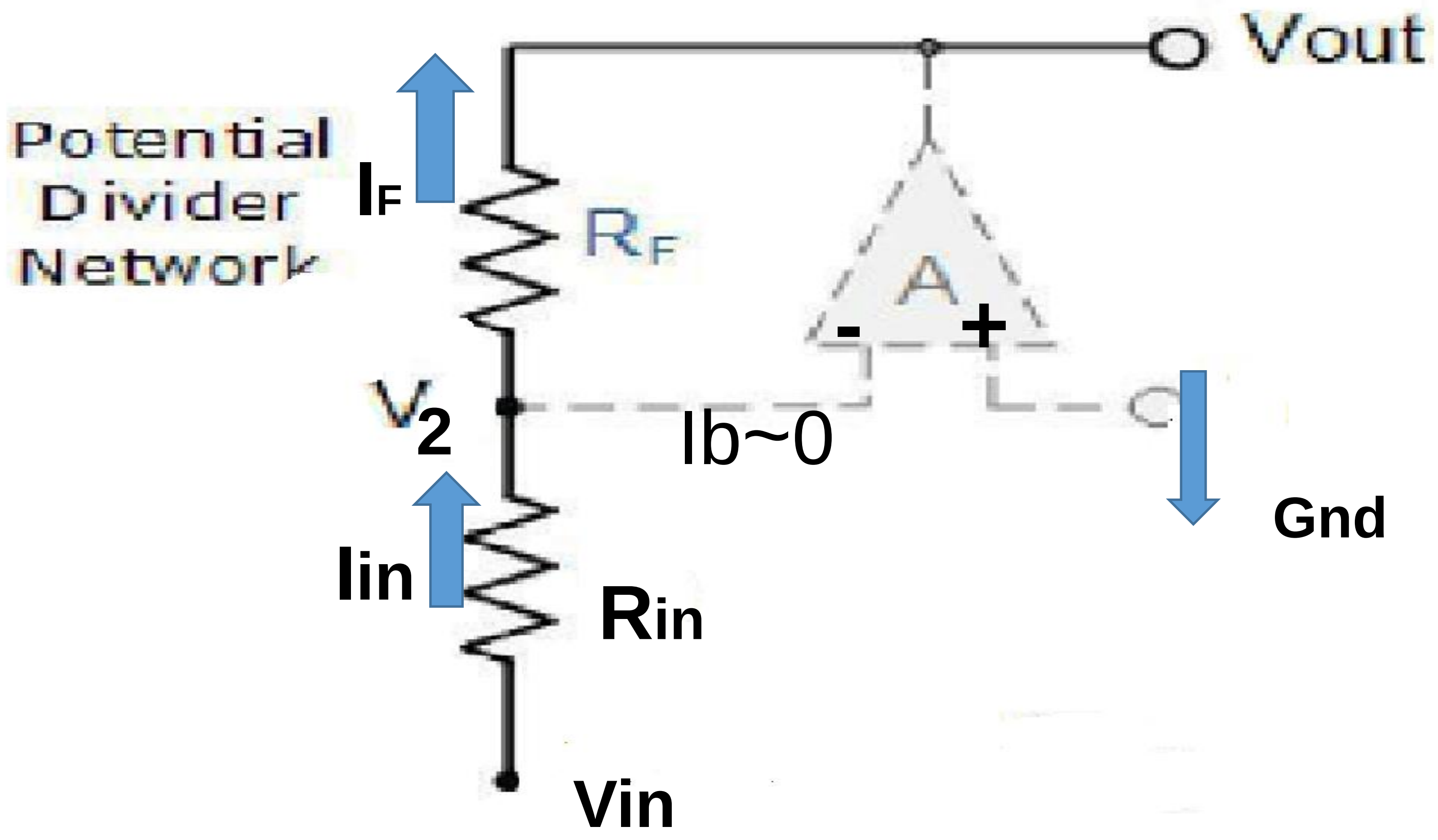
1) No Current Flows into the Input Terminals

2) The Differential Input Voltage is Zero as V1 = V2 = 0 (Virtual Earth)

- Then by using these two rules we can derive the equation for calculating the closed-loop gain of an inverting amplifier, using first principles.
- Current (i) flows through the resistor network as shown.

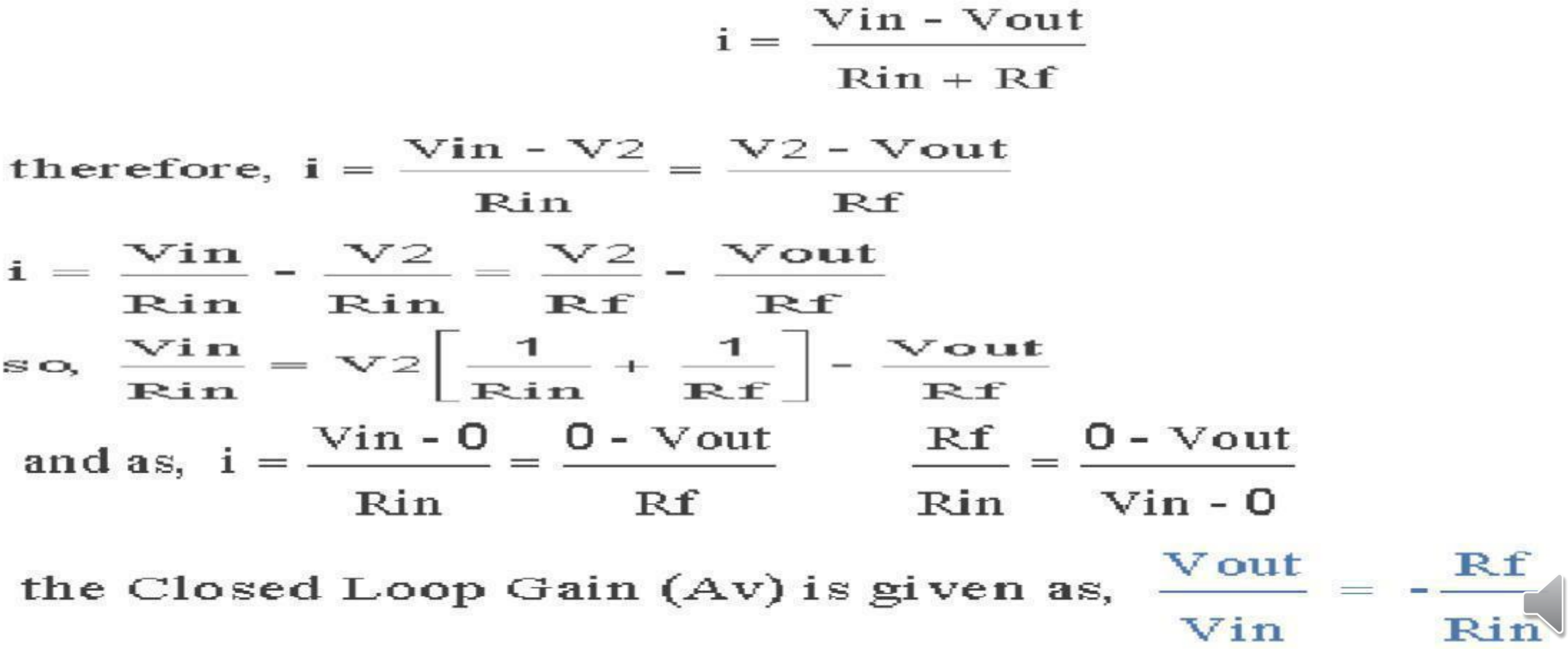
- $Av = Avf = Vo/ Vin = - Rf/ Rin$

Equivalent circuit of Inverting Amplifier



Because of this virtual earth node the input resistance of the amplifier is equal to the value of the input resistor.

Rin and the closed loop gain of the inverting amplifier can be set by the ratio of the two external resistors.



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

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

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

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

and as, $i = \frac{Vin - 0}{Rin} = \frac{0 - Vout}{Rf}$ $\quad \frac{Rf}{Rin} = \frac{0 - Vout}{Vin - 0}$

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

$$A_V = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}$$

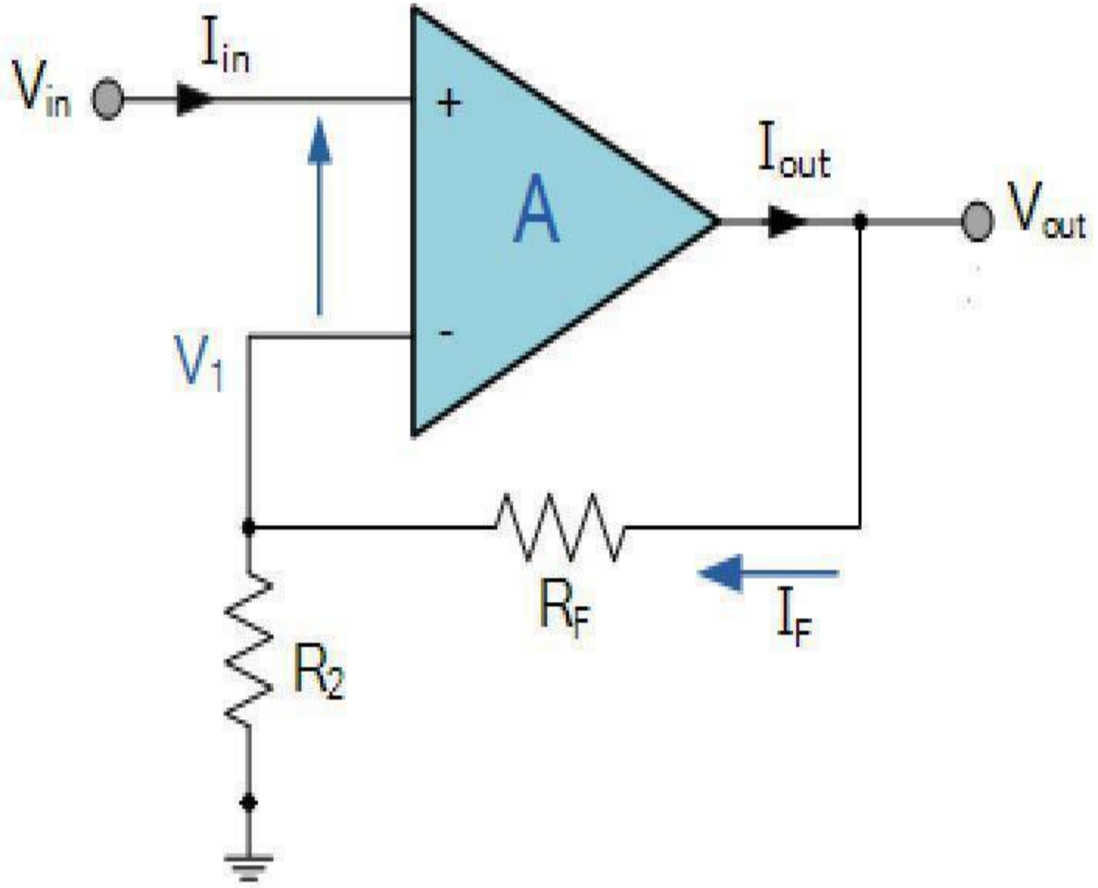
- Then, the Closed-Loop Voltage Gain of an Inverting Amplifier is given as and this can be transposed to give Vout as:

$$V_{out} = -\frac{R_f}{R_{in}} * Vin$$

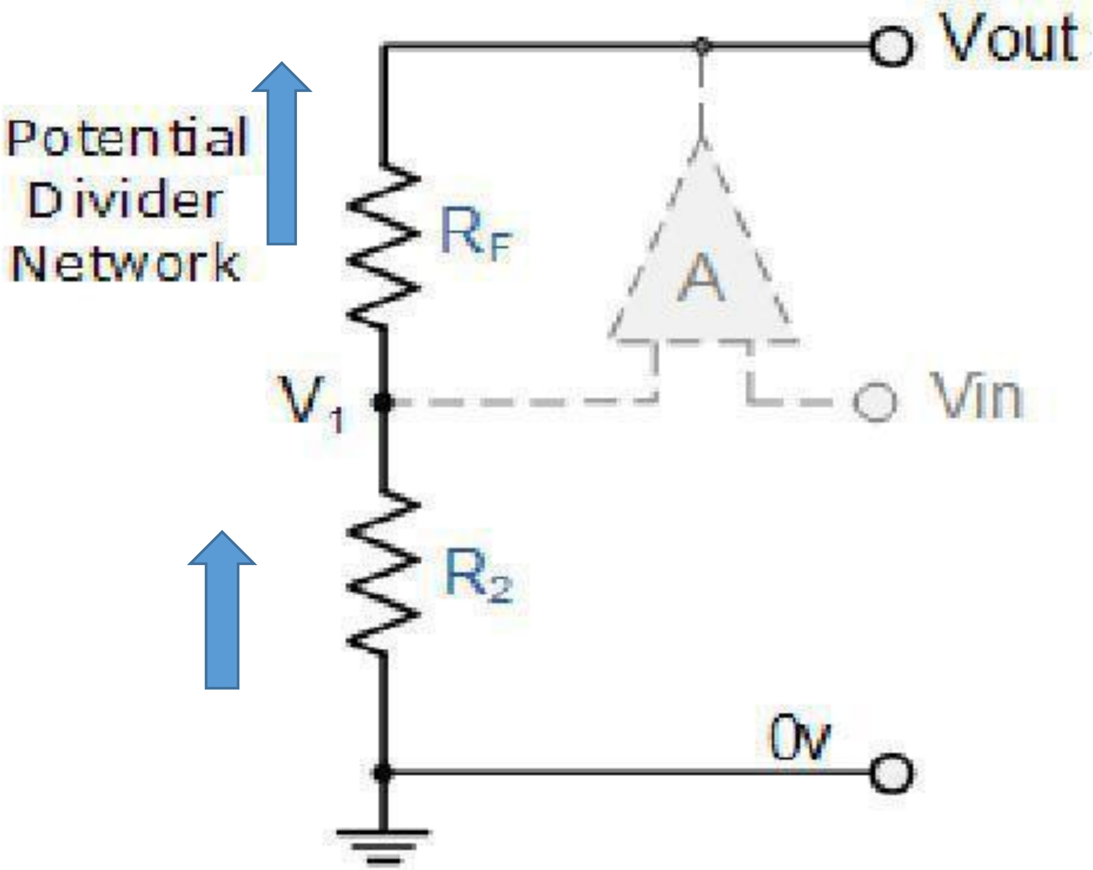
The negative sign in the equation indicates an inversion of the output signal with respect to the input as it is 180o out of phase. This is due to the feedback being negative in value.

Prob. Design Inverting Amplifier for a Gain of 10.

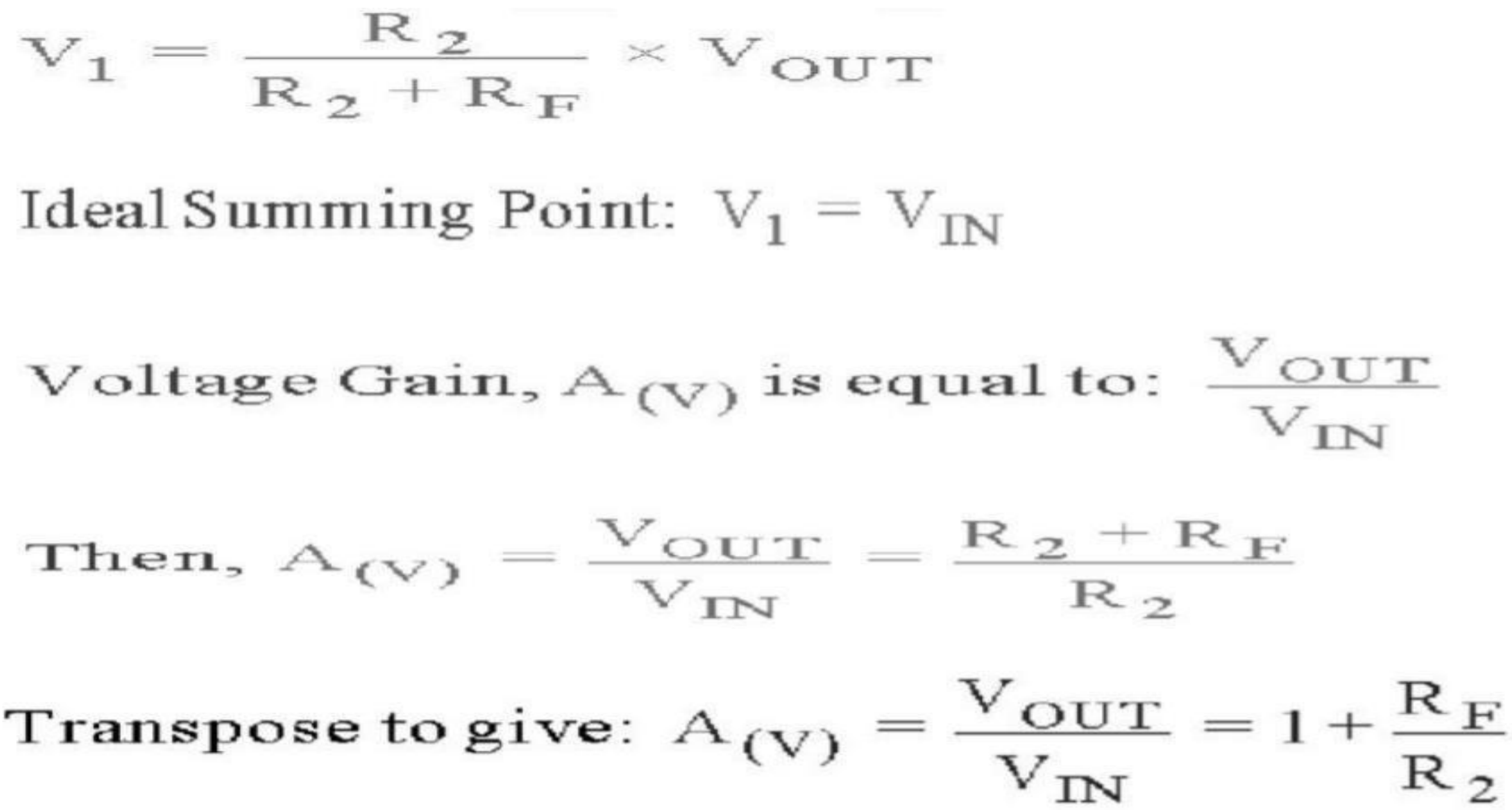
2b. Closed Loop Non–Inverting Amplifier



Equivalent circuit of Non- Inverting Amplifier



Mathematical Analysis



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

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

Voltage Gain, $A_{(V)}$ is equal to: $\frac{V_{OUT}}{V_{IN}}$

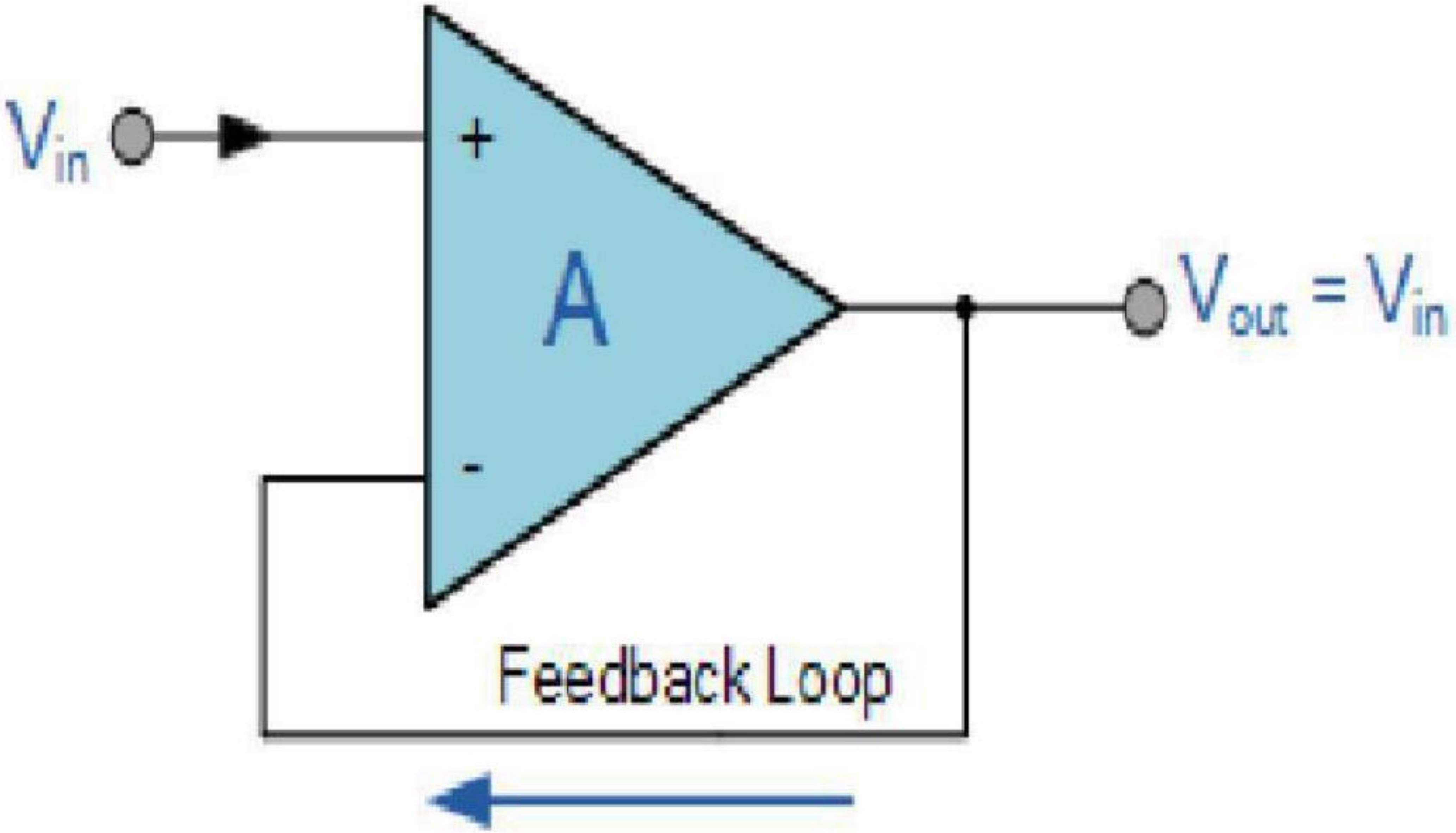
Then, $A_{(V)} = \frac{V_{OUT}}{V_{IN}} = \frac{R_2 + R_F}{R_2}$

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

- We can see from the equation above, that the overall closed-loop gain of a non-inverting amplifier will always be greater but never less than one (unity),
- it is positive in nature and is determined by the rati**o of the values of Rƒ and R2. If the value of the feedback resistor Rƒ is zero, the gain of the amplifier will be exactly equal to one (unity). If resistor R2** is zero the gain will approach infinity, but in practice it will be limited to the operational amplifiers open-loop differential gain, (Ao).

$$\mathrm{Af} = \mathrm{Avf} = \mathrm{Vo}/\ \mathrm{Vin} = 1 + \mathrm{Rf}/\ \mathrm{Rin}$$

2c. Voltage Follower / Unit Gain Buffer



- **If we made the feedback resistor, Rƒ equal to zero i.e (Rƒ = 0), and resistor R2 equal to** infinity i.e. **(R2 = ∞) as shown in fig , then the circuit would have a fixed gain o**f "1", as all the output voltage would be present on the inverting input terminal (negative feedback).
- This would then produce a special type of the non-inverting amplifier circuit called a “**Voltage Follower”** or also called a **“unity gain buffer".**