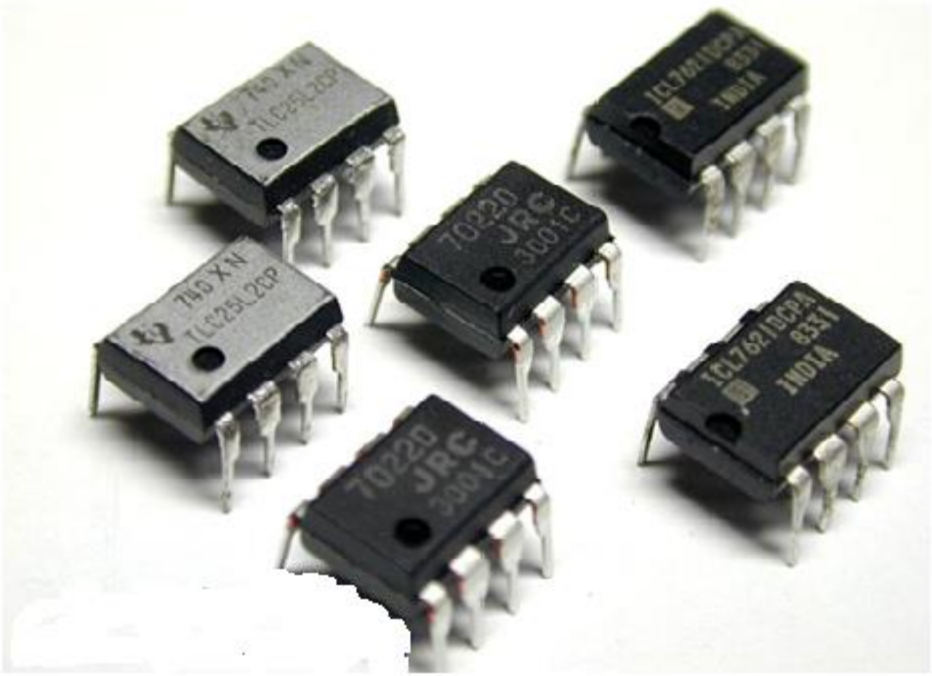
OPERATIONAL AMPLIFIER (Op-amp)



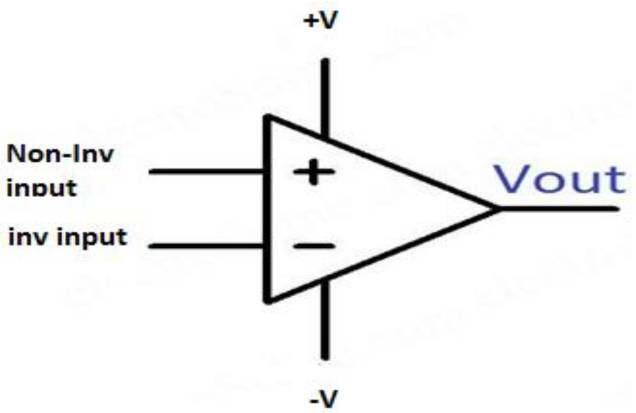
Introduction

- **OP-amp is an IC that uses external voltage to amplify the input through a high gain.**
- **A amplifying device designed to be used with the proper selection of external feedback components.**
- **It is a high-gain electronic voltage amplifier with a differential input and a single-ended output.**
- **It was originally used to perform mathematical operations like addition, subtraction, differentiation, integration etc.**
- ***One of the most useful circuit blocks for analog design and analog signal processing.***
- ***Low cost Electronic circuit***
- ***Consists of Transistors, Diodes, Capacitors and resistors and* can be combined with external discrete components to create a wide variety of Signal processing circuits.**
- **Commonly used for Linear and non-linear applications.**
- **They are two port network in which the output voltage or current is directly proportional to either input voltage or current.**
- **Op-amp is available in different package styles.**

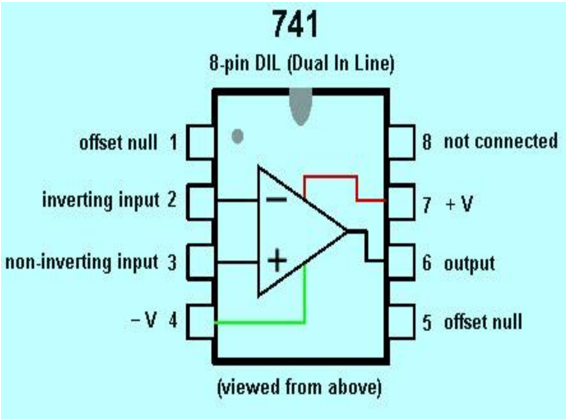
What is Op-amp?

- **Monolithic Integrated Circuit Op-Amp First created in 1963**
- **µA702 by Fairchild Semiconductor, µA741 created in 1968 - widely used due to its ease of use**
- **Op-amps (amplifiers/buffers in general) are drawn as a triangle in a circuit schematic**
- **There are two inputs such as inverting and non-inverting input and a single output.**
- **Also power connections (note no explicit ground), 8 pin, dual in-line package**

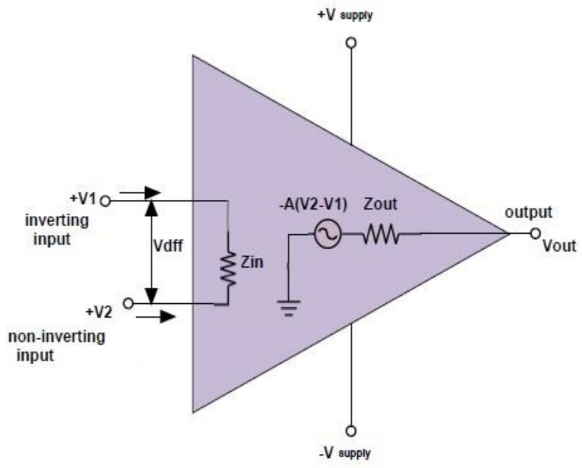
Circuit symbol



Pin Details

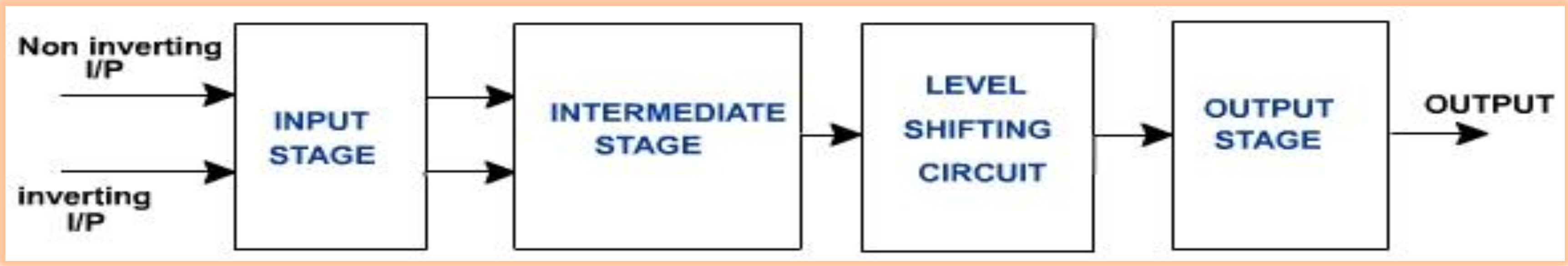


Equivalent circuit of an op-amp



Theoretically, the dc output voltage will be zero if both the inputs of the 741 IC are connected to the ground. But in practice, a small dc output may appear due to minor internal unbalances. But for critical conditions, the output voltage can be set precisely to zero by connecting a 10K potentiometer between terminals marked "offset-null".

Block diagram representation of Typical Op-amp



1.Input stage: Dual input, Balanced output differential amplifier
provides → most voltage gain of op-amp
→ input resistance of op-amp

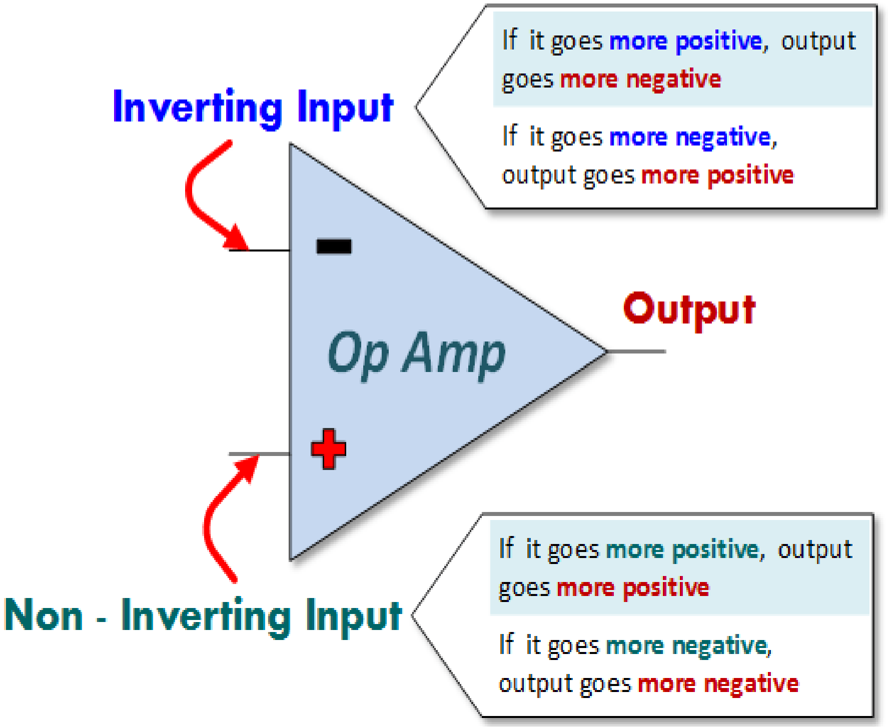
2.Intermediate stage:
Dual input, unbalanced output differential amplifier
drives the output of first stage
Direct coupling → dc voltage well above the ground level

3.Level Shifting Circuit: DC voltage to zero with respect to ground

4.Output stage: increases the output voltage swing
provides low resistance
raises the current supply capability of an op-amp.

What makes Op-amp different from other amplifiers ?

- **Op amp is a differential amplifier having very high gain.**
- **Providing gain to even for small signals.**
- **Very high input impedance**
- **Very low output impedance**
- **High CMRR**
- **High bandwidth**
- **Able to amplify both AC and DC**
- **Low noise**
- **Low power consumption.**
- **Short circuit and overload protection provided.**
- **No external frequency compensation is required.**
- **Also does not need any external compensation for phase component.**
- **No latch-up problem.**
- **Absolute value circuit.**
- **Available in various operating temperature ranges**
- **Used as a building block for many devices and circuits such as Amplifiers, Integrators, summers,**



Ideal OP-AMP

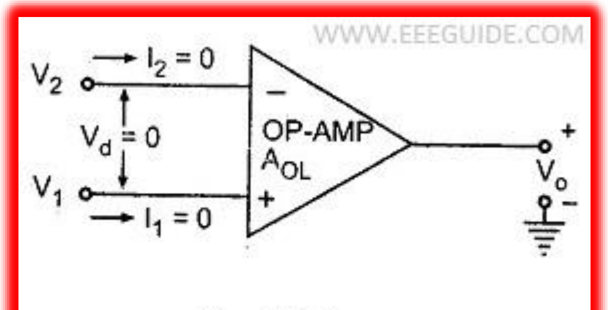
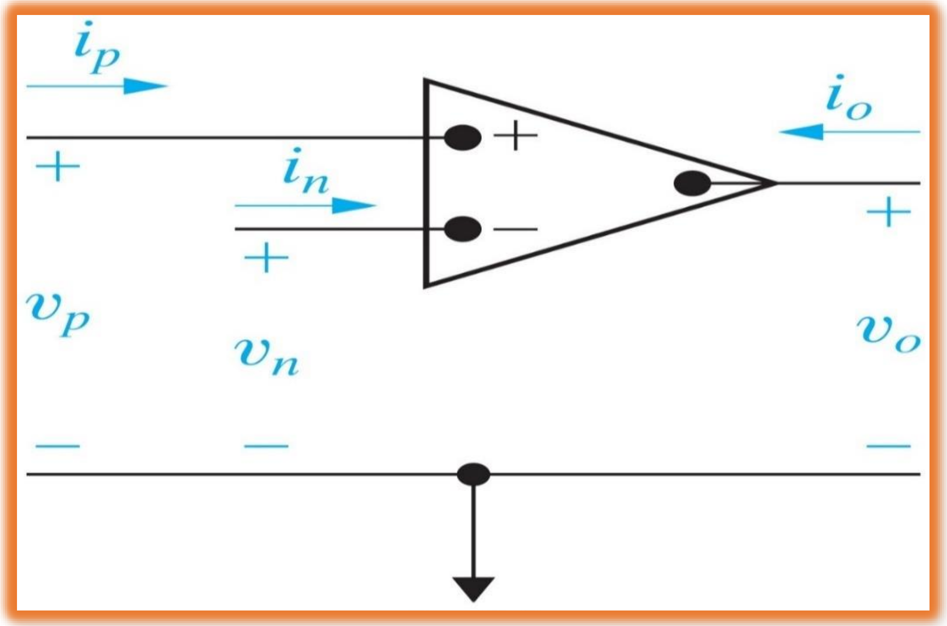


Fig. Ideal op-amp

- It performs open loop operation, there is no feedback path.
- An ideal op-amp draws no current at both the input terminals i.e. ip = in= 0.
- Input impedance is infinite. Any source can drive it and there is no loading on the driver stage.
- Gain is very high, so it is unstable.



$$v_o = A(v_p - v_n)$$

$$R_{in} \rightarrow \infty$$

$$A \rightarrow \infty$$

$$v_p = v_n$$

$$i_p = i_n = 0$$

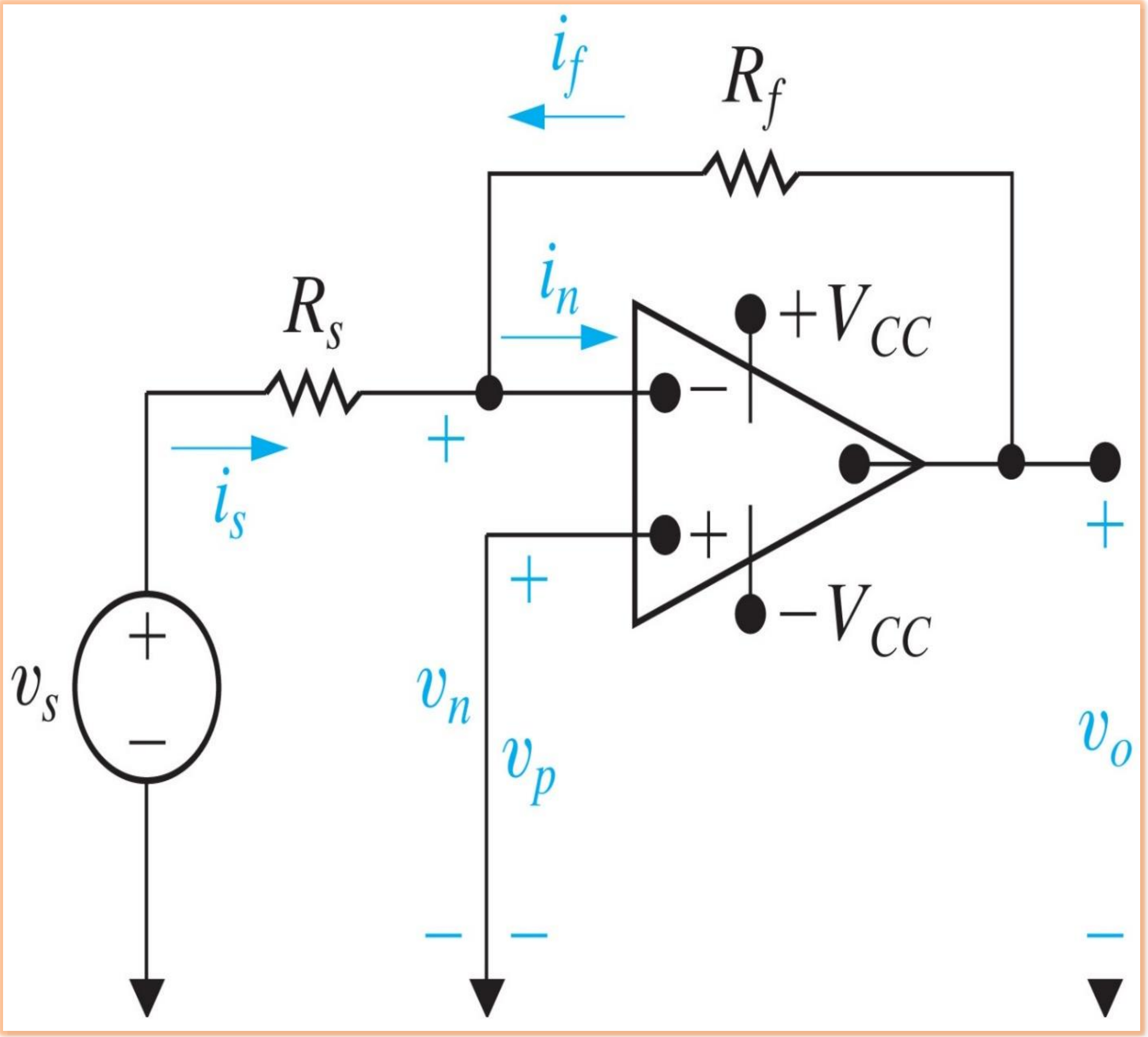
Basic Characteristics of an Ideal Op-amp

- Input impedance is infinite.
- Differential inputs that stick together- In the ideal op-amp, a voltage applied to one input also appears at the other input.
- Infinite Bandwidth-The ideal op-amp will amplify all signals from DC to the highest AC frequencies.
- Zero output impedance -The ideal op-amp acts as a perfect internal voltage source with no internal resistance
- Zero noise contribution -In the ideal op-amp, zero noise voltage is produced internally. Practical op-amp are affected by several noise sources, such as resistive and semiconductor noise
- Zero DC output offset - The output offset is the output voltage of an amplifier when both inputs are grounded. The ideal op-amp has zero output offset, but real op-amps have some amount of output offset voltage

Closed Loop operation of Op-amp

1. Inverting Amplifier
2. Non-inverting amplifier

Inverting amplifier

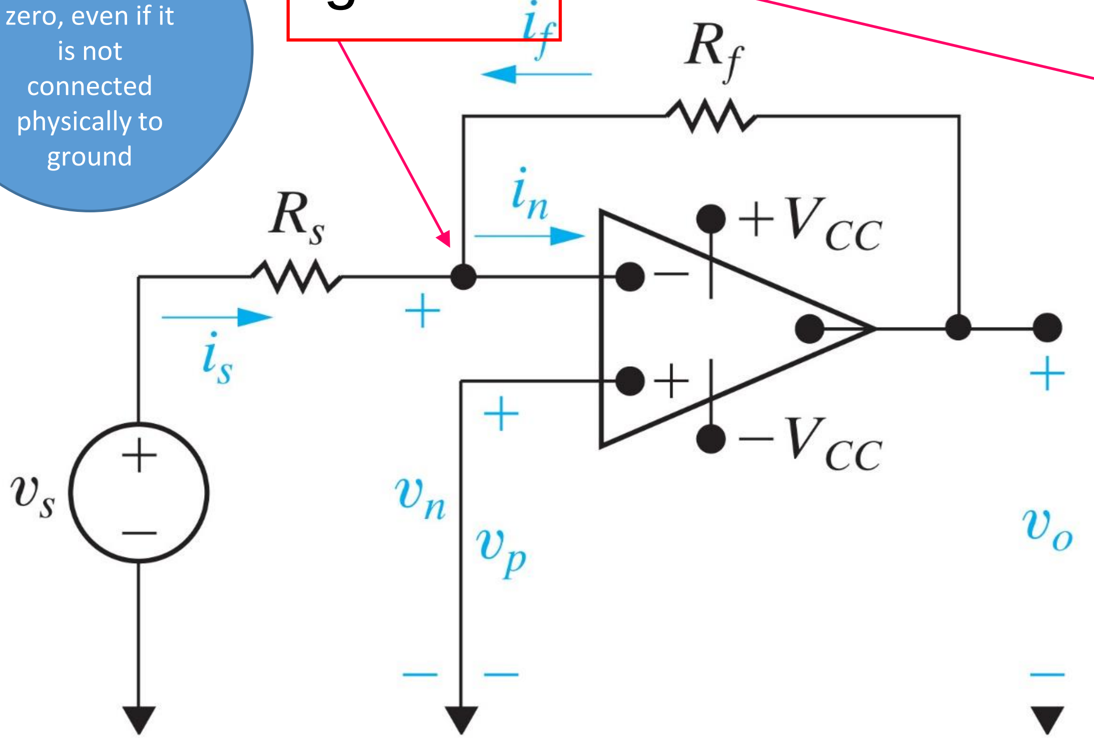


- The operational amplifier is connected with feedback to produce a closed loop operation.
- The input voltage is applied at the inverting input terminal of the op-amp.
- Here, “No current flows into the input terminal” and that “Vp always equals Vn”.
- Negative feedback weaken the input signal.
- It reduces gain thus stability increases.
- Reduces the effect of input offset voltage Increase bandwidth

Analysis Using the Ideal OP AMP (inverting amplifier)

Voltage is almost equal to zero, even if it is not connected physically to ground

"Virtual" ground



$$i_s + i_f = i_n$$

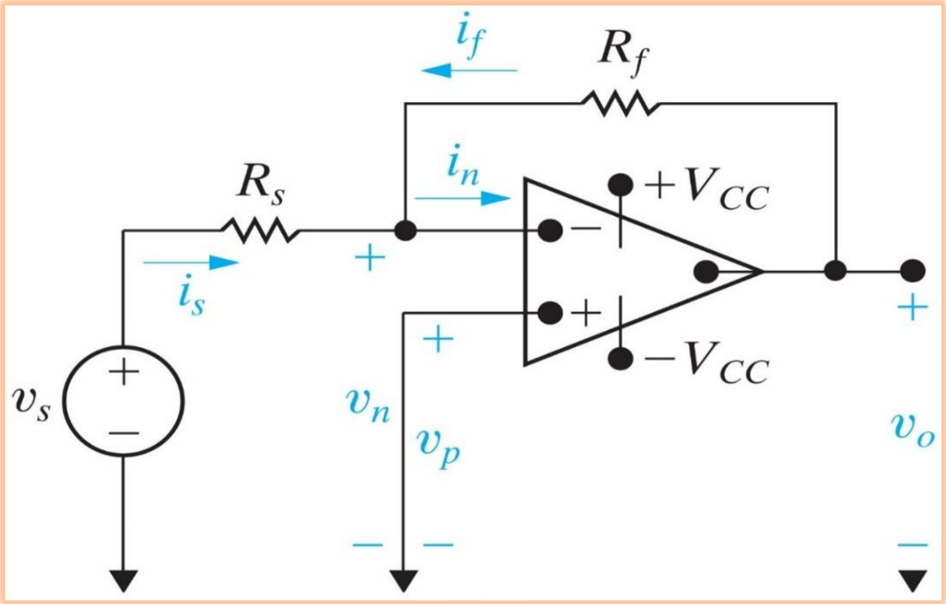
$$v_n = v_p = 0$$

$$i_s = \frac{v_s}{R_s}$$

$$i_f = \frac{v_o}{R_f}$$

Virtual Ground	Real Ground
Virtual Ground is a concept that made for easy explanation and calculation purposes.	Real Ground is a terminal which is physically connected to ground or earth which acts as the reference point for the entire circuit.
Voltage is **approximately** Zero	Voltage is Zero
Not able to sink infinite current	It is an infinite current sink
Not electrically connected to Ground	Electrically connected to Ground

Analysis continued

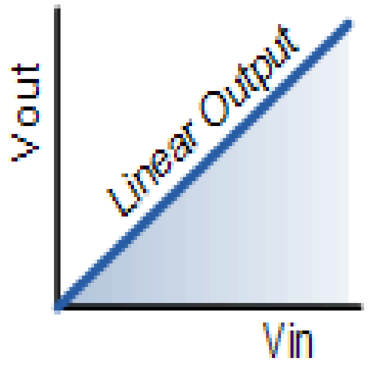


$$i_n = 0$$

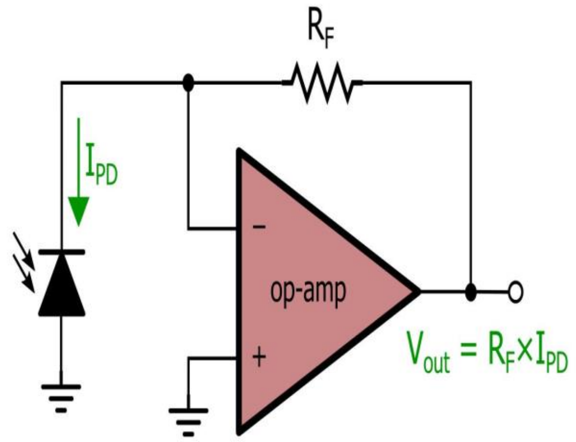
$$i_f = -i_s$$

$$\frac{v_o}{R_f} = -\frac{v_s}{R_s}$$

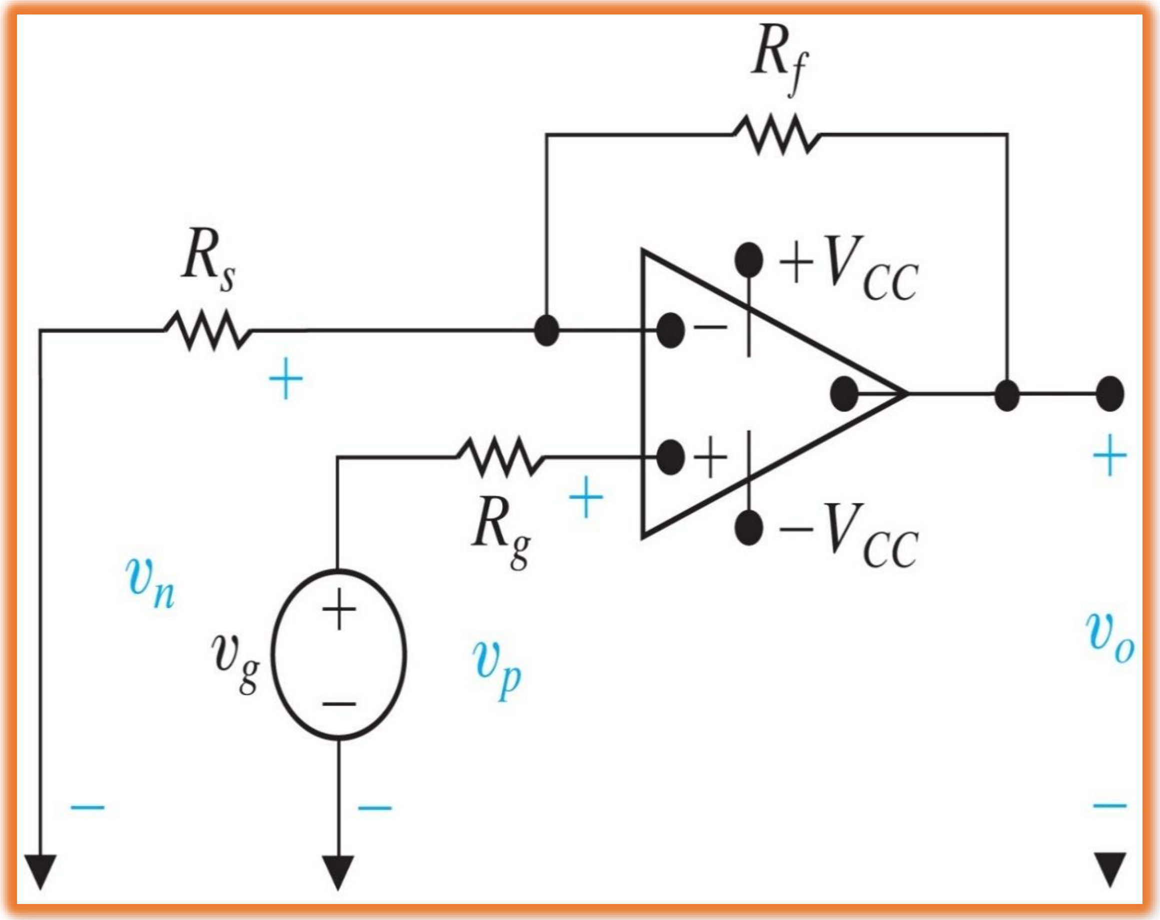
$$v_o = -\frac{R_f}{R_s} v_s \longrightarrow \text{Eq.1`}$$



- The eq.1 indicates an inversion of the output signal with respect to the input as it is 180^o out of phase. This is due to the feedback being negative in value.
- *Vo* shows that the circuit is linear in nature for a fixed amplifier = Vin x Gain. This property useful for converting a smaller sensor signal to a much larger voltage.
- The application of an inverting amplifier is that of a "transresistance amplifier" circuit.
- Can be used in low-power applications to convert a very small current generated by a photo-diode or photo-detecting device into a usable output voltage which is proportional to the input current

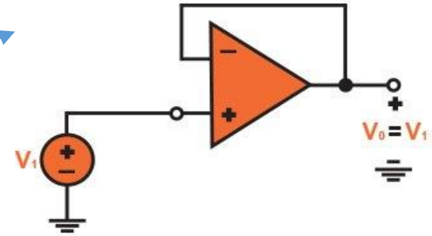


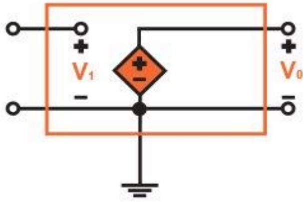
Non-Inverting Amplifier



- The Operational amplifier is connected with feedback to produce a closed loop operation.
- The input voltage is applied at the non-inverting input terminal of the op-amp.
- The important application of non-inverting amplifier is Voltage follower or buffer. Here the output follows the input.
- The high input impedance has a property that plays a key role of the noninverting configuration.
- This impedance allows the circuit to be used as a buffer amplifier that connects to a source that goes from a high to low impedance load.

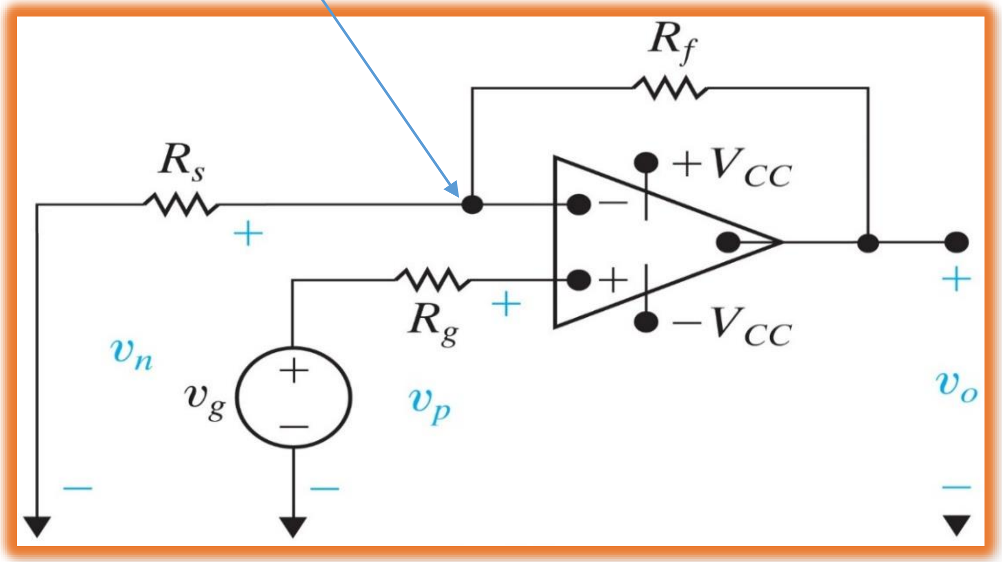
For the ideal case, Vo=Vi, Rin=infinite, Rout=0





Analysis Using the Ideal OP AMP (Non-inverting amplifier)

“Virtual Short



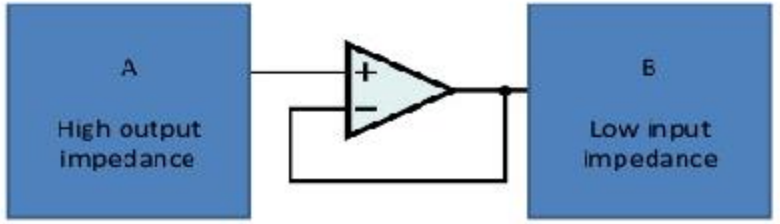
$$v_p = v_g$$

$$v_n = v_p = v_g = v_o \frac{R_s}{R_s + R_f}$$

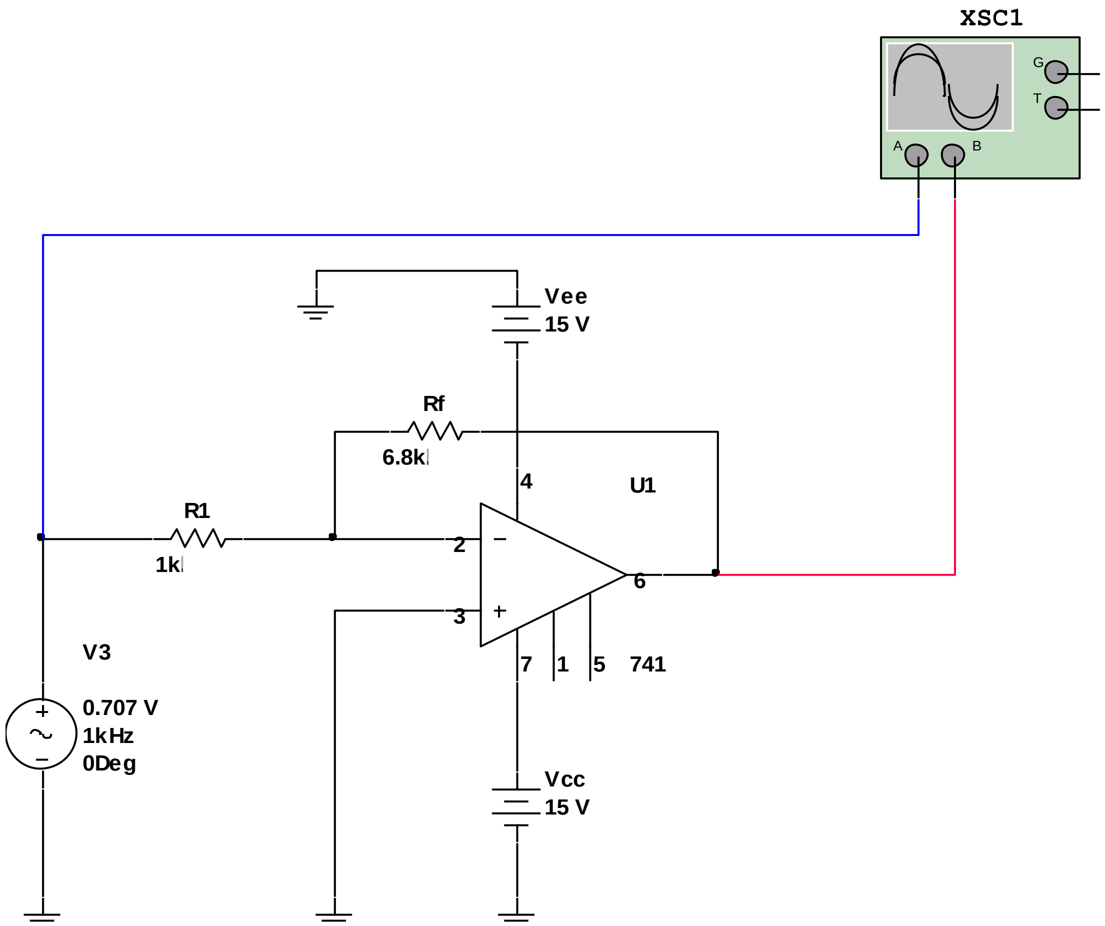
$$v_o = \frac{R_s + R_f}{R_s} v_g$$

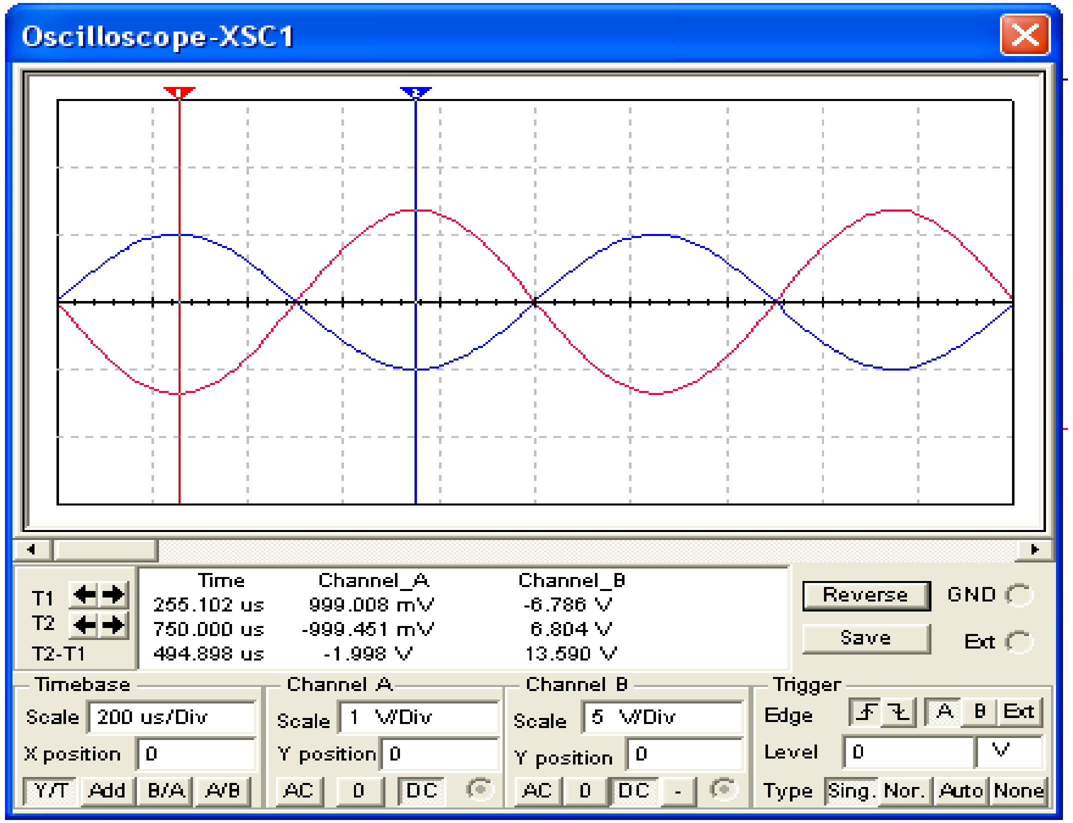
$$v_o = \left(1 + \frac{R_f}{R_s}\right) v_g \longrightarrow \text{Eq.2}$$

- Output signal of non-inverting op amp is in-phase with the input signal applied.
- Uses negative feedback connection, but instead of feeding the entire output signal to the input, only a part of Output signal voltage is fed back as input to the inverting input terminal of the op-amp.
- Mainly useful for high impedance applications



In a Practical case- Inverting Amplifier

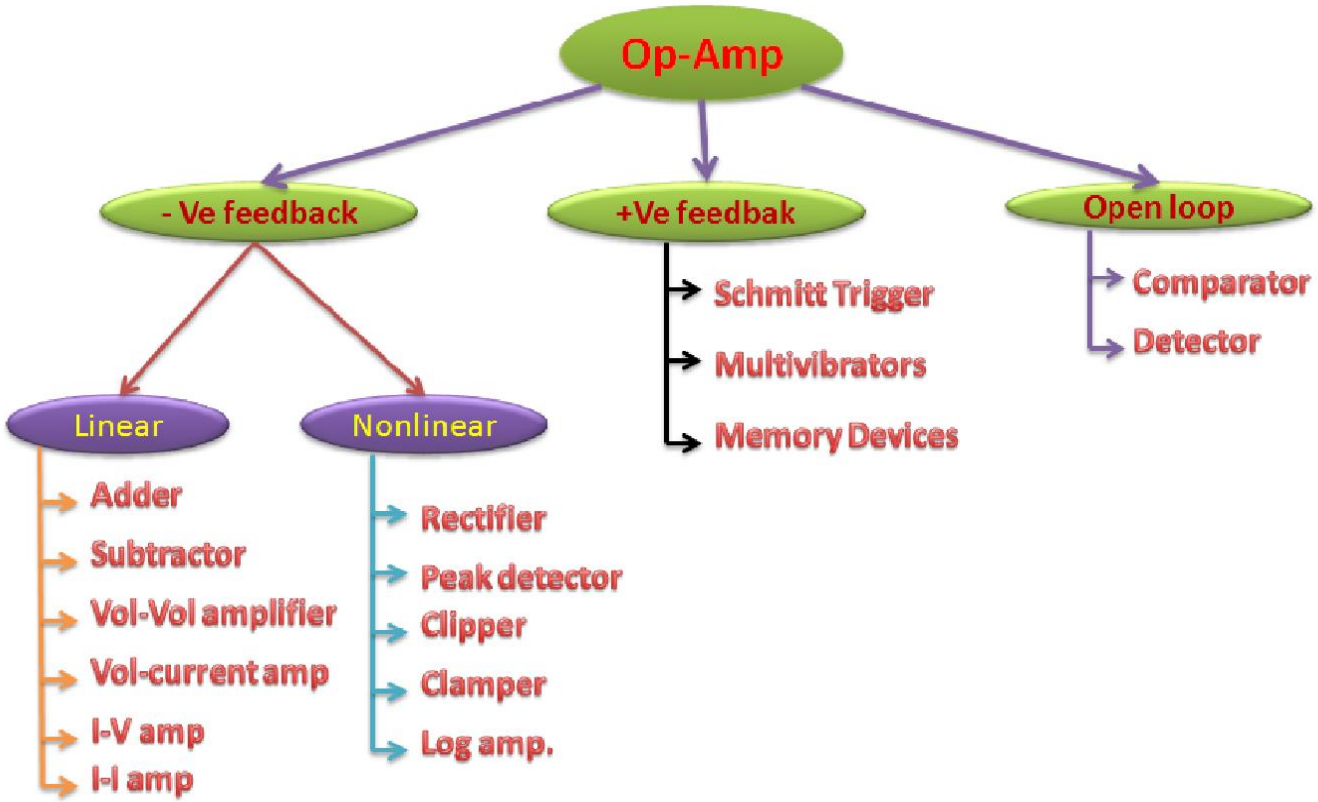


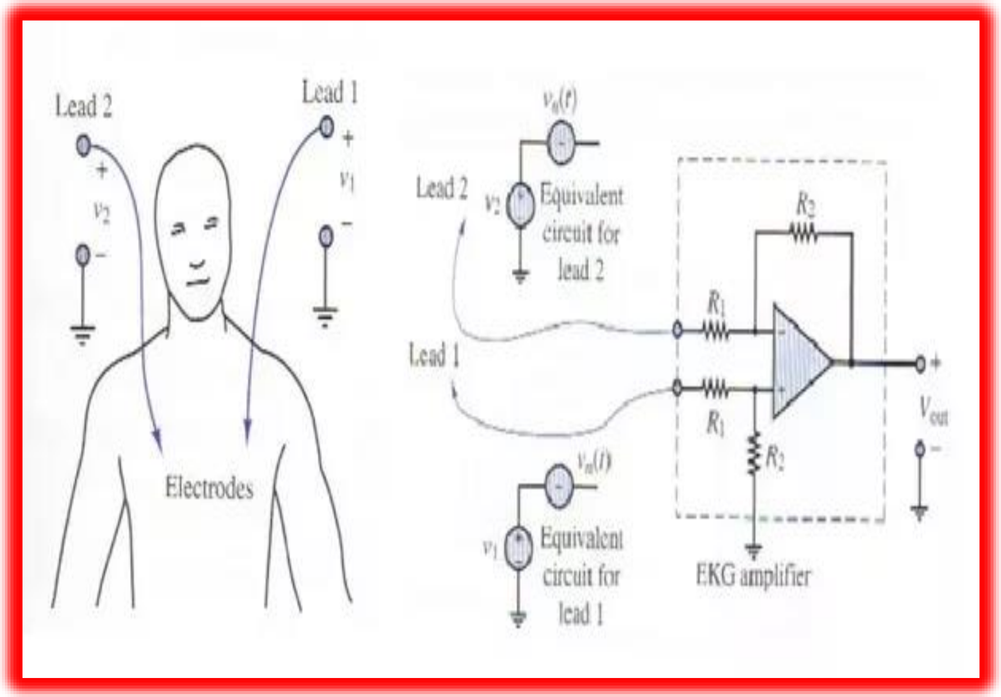


— indicates the input applied to the inverting input of an op amp

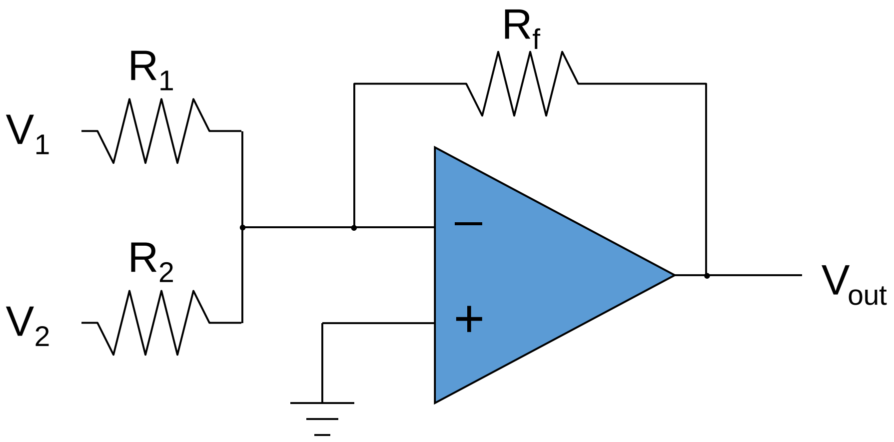
— indicates the output from amplifier

Applications of Op-amp



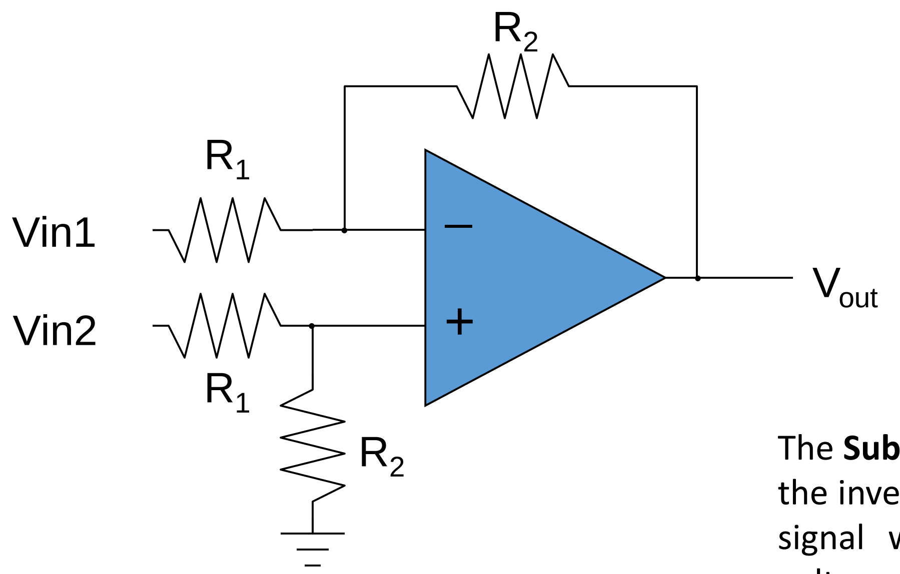


Analysis of Summing Amplifier(only for two inputs)



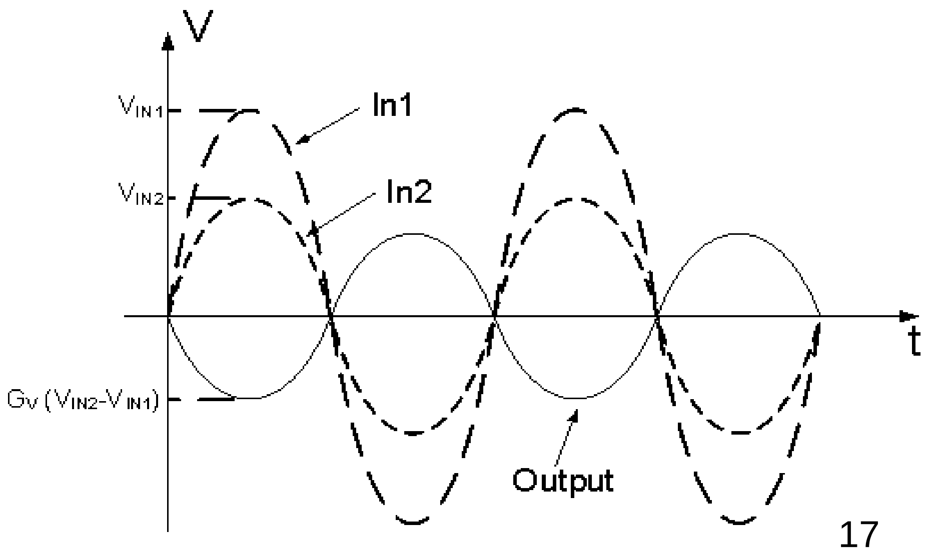
- Much like the inverting amplifier, but with two input voltages
  - inverting input still held at virtual ground
  - I_1 and I_2 are added together to run through R_f
  - so we get the (inverted) sum: $V_{out} = -R_f \times (V_1/R_1 + V_2/R_2)$
    - if $R_2 = R_1$, we get a sum proportional to $(V_1 + V_2)$, where A represents gain of the amplifier, A=Rf/R;
- Can have any number of summing inputs
  - Make our D/A converter in this way.

Analysis of Subtracting Amplifier (Subtractor)

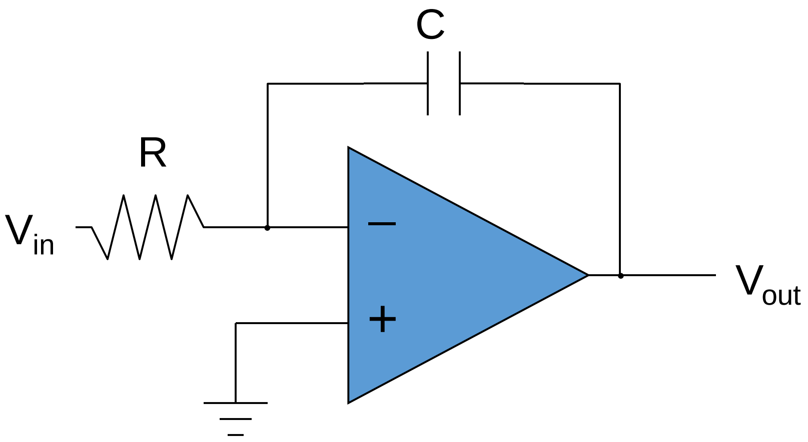


The **Subtractor** also called a differential **amplifier**, **uses** both the inverting and non-inverting inputs to produce an output signal which is the difference between the two input voltages V1 and V2 allowing one signal to be subtracted from another.

- The non-inverting input is a simple voltage divider:
  - $V_{node} = Vin2*R_2/(R_1 + R_2)$
  - so $V_{out} = (R_2/R_1)(Vin2 – Vin1)$, where Gv= R2/R1;
  - therefore we difference V^+ and V^-



Analysis of Low-pass filter (integrator) using opamp



- $I_f = V_{in}/R$, so $C \cdot dV_{cap}/dt = V_{in}/R$

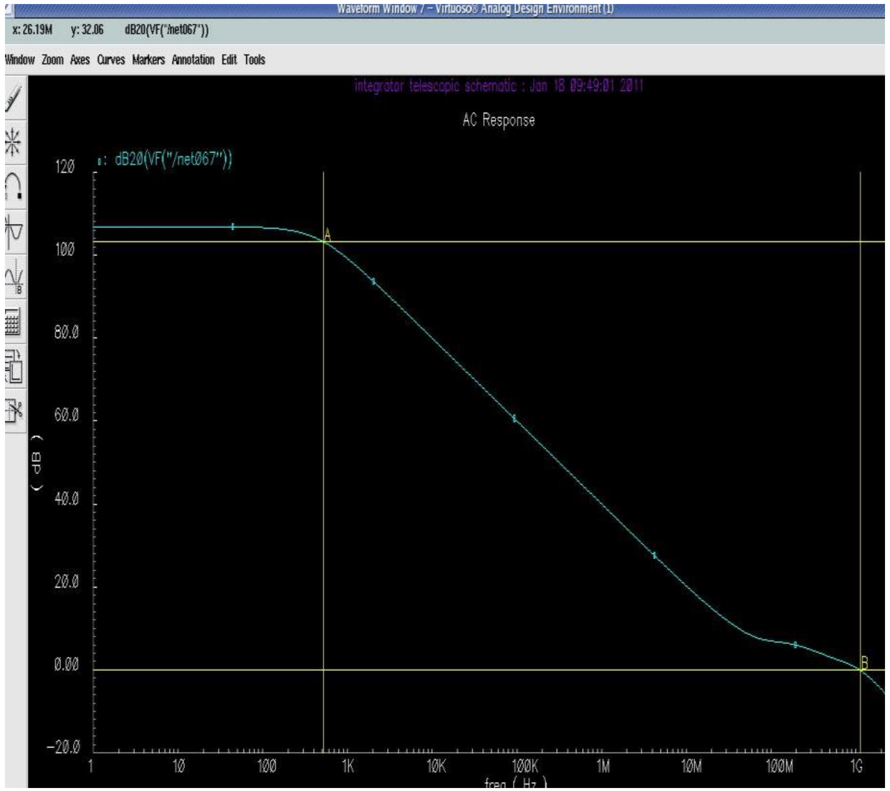
and since left side of capacitor is at virtual ground

$$-dV_{out}/dt = V_{in}/RC$$

so

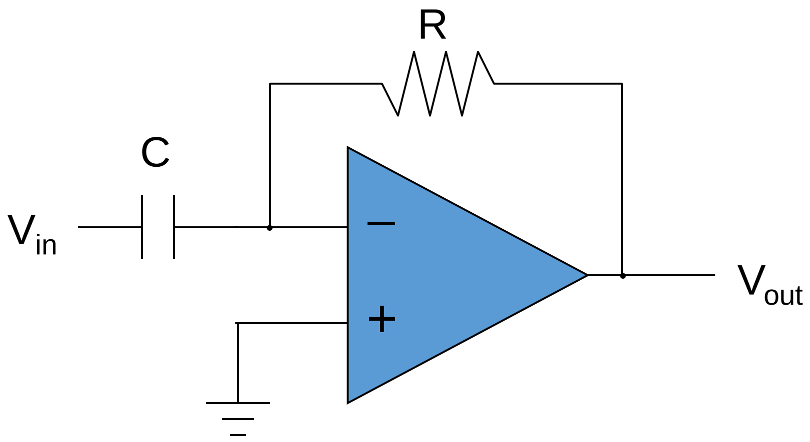
$$V_{\text{out}} = -\frac{1}{RC}\int V_{in}dt$$

- and therefore we have an integrator (low pass)

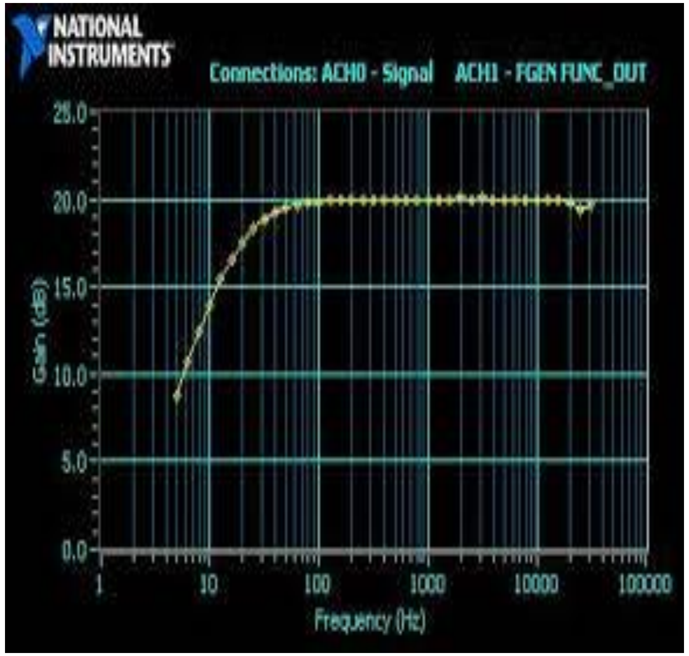


Frequency response of Integrator

Differentiator (high-pass filter) using opamp



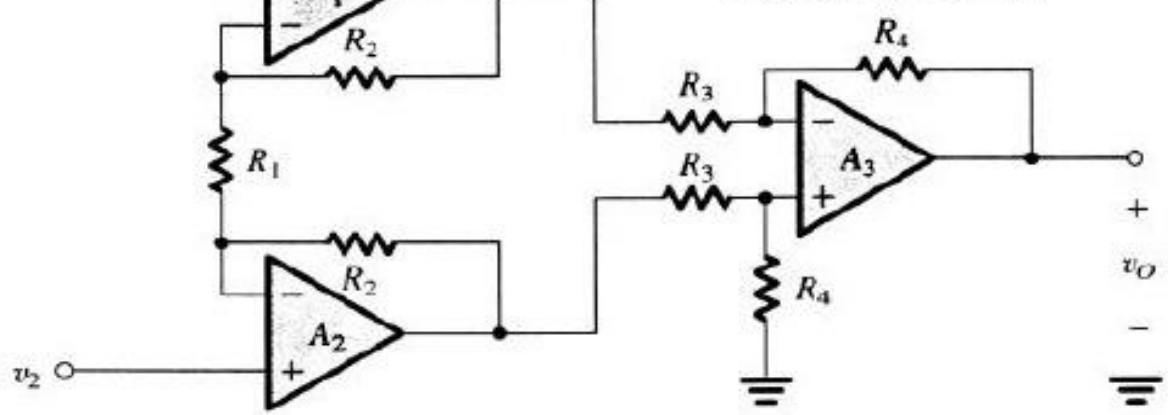
- For a capacitor, $Q = CV$, so $I_{cap} = dQ/dt = C \cdot dV/dt$
    - Thus $V_{out} = -I_{cap}R = -RC \cdot dV/dt$
- So we have a differentiator, or high-pass filter
    - if signal is $V_0 \sin \omega t$, $V_{out} = -V_0 RC\omega \cos \omega t$
    - the ω-dependence means higher frequencies amplified more



Frequency response of Differentiator

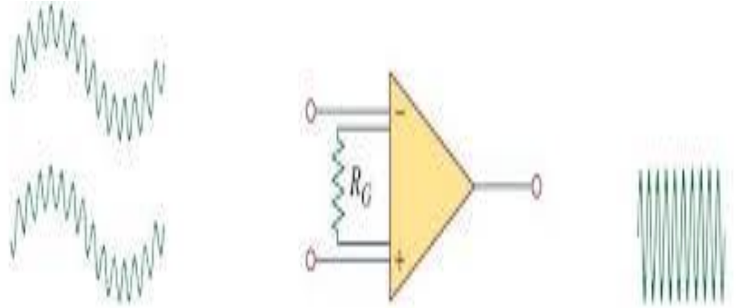
Instrumentation amplifier

- Very high input impedance.
- Gain can be set with only one resistor.
- Can optimize CMRR.



$$A_V = -\frac{R_4}{R_3}\left(1 + \frac{2R_2}{R_1}\right)$$

For one-resistor gain adjust, set $R_4 = R_3$ and fix R_2.



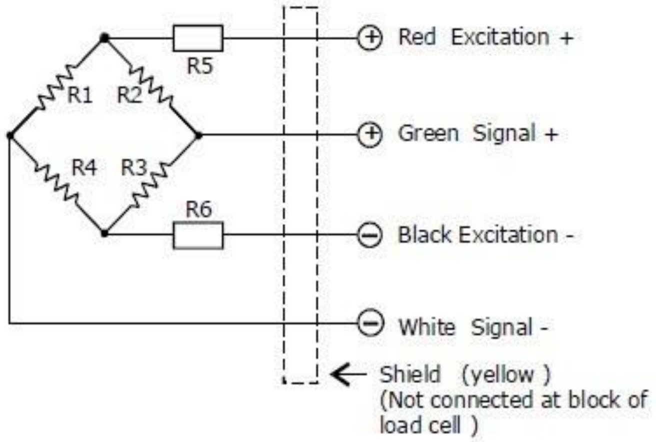
Small differential signals riding on larger common-mode signals

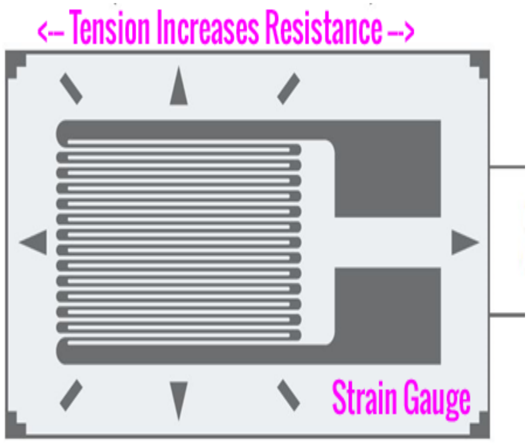
Instrumentation amplifier

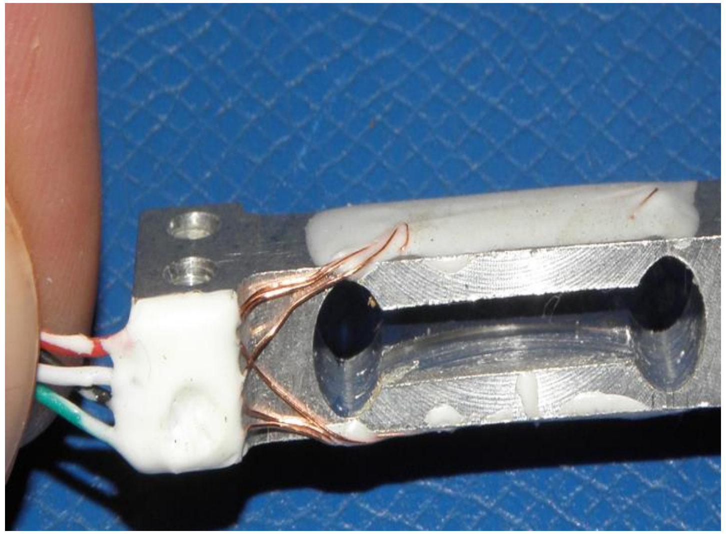
Amplified differential signal, No common-mode signal

Application of Instrumentation amplifier

- A load cell is made from strain gages attached to a metal frame and essentially we are measure very minute changes in length of the copper traces due to the stress on them – a very tiny signal!
- Also because the gauges act as a voltage divider across 15 volts, the very tiny signal we want is superimposed on top of the relatively huge 7.5V. The ability to strip the huge 7.5V DC signal that is common to both inputs is known as the Common Mode Rejection Ratio and is an important aspect when picking an instrumentation amplifier.
- we can easily see the effects of applying a force to the load cell. As this is a wide band amplifier and there is no real filtering going on you can see what is essentially amplified noise present in the oscilloscope trace.
- In a real weighing application there would be judicious use of shielding and some low pass filtering applied to create a consistent DC voltage representing the weight on the load cell.
- Connecting the load cell to the evaluation board with opamp set for a gain of particular value does give us enough amplification



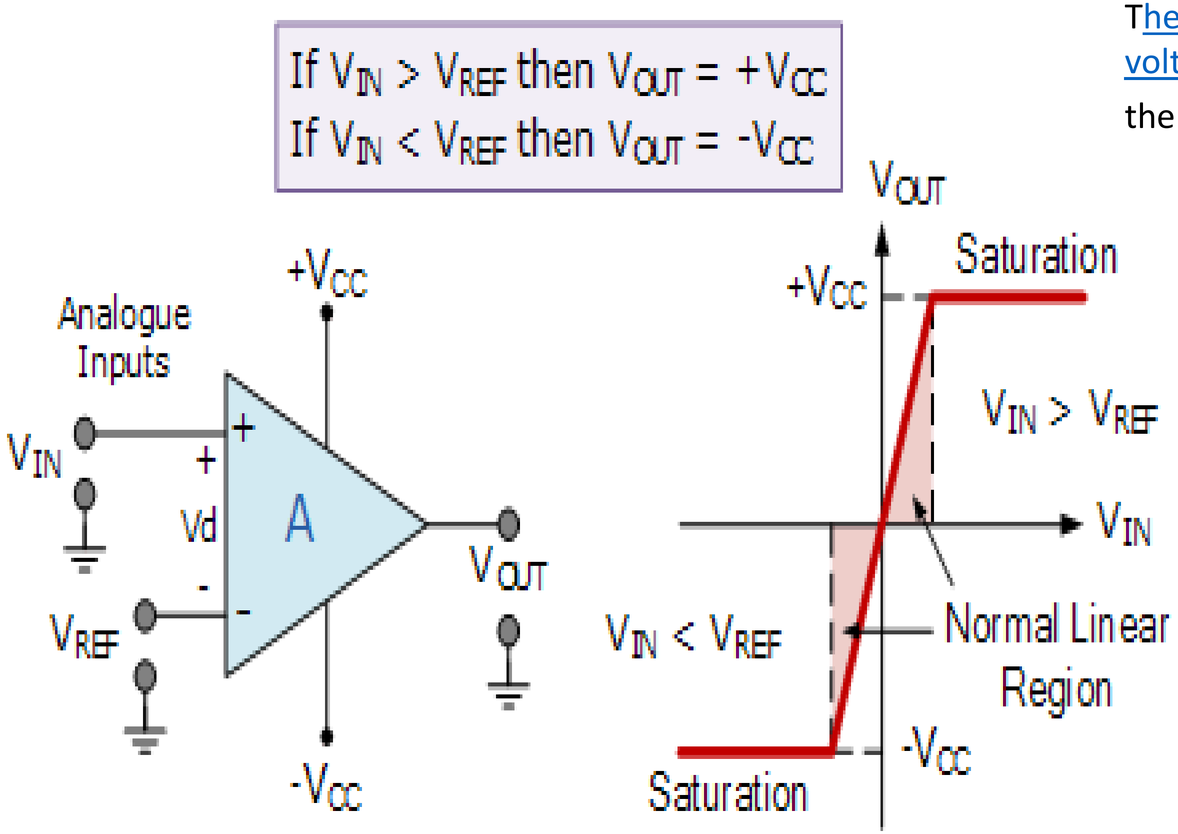




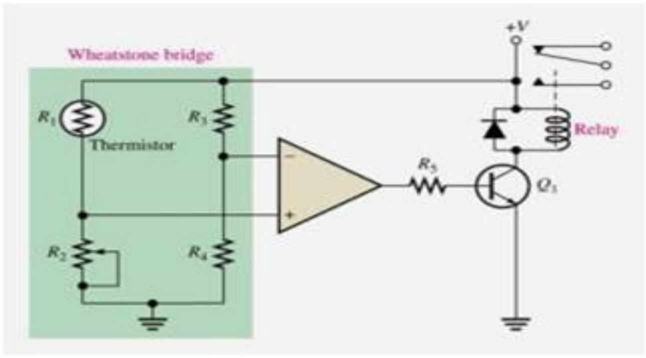
Load cell Arrangement

Comparator and its applications

The comparator is used to compare two voltages or currents which are given at the two inputs of the comparator.



Over Temperature Sensing Circuit



Advantages/Disadvantages

Advantages:

- Cheap, easy to use, effective
- OP-AMP is an universal amplifier
- Voltage comparators.
- Precision rectifiers.
- Analog to digital converters

Disadvantages:

- Ideal not possible, phase shift at high frequencies
- Most OP-AMP are Designed to for lower power operation
- For high output desire then the OP-AMP specifically designed for that purpose must be seen.
- Most commercial OP-AMP shuts off when the load resistance is below the specified level.

Applications: A/D Conversion, Filtering, any digital Circuit, Controller design.