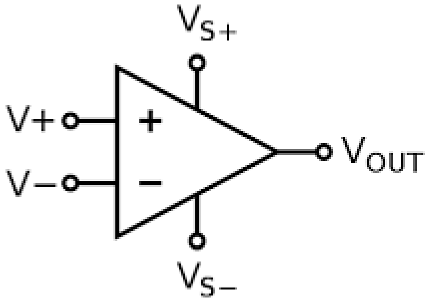
Electronics

Operational Amplifier (Op-Amps)



Operational amplifiers are linear devices that have all the properties required for nearly ideal DC amplification and are therefore used extensively in signal conditioning, filtering or to perform mathematical operations such as add, subtract, integration and differentiation.

An **Operational Amplifier**, or op-amp for short, is fundamentally a voltage amplifying device designed to be used with external feedback components such as resistors and capacitors between its output and input terminals. These feedback components determine the resulting function or “operation” of the amplifier and by virtue of the different feedback configurations whether resistive, capacitive or both, the amplifier can perform a variety of different operations, giving rise to its name of “Operational Amplifier”.

An *Operational Amplifier* is basically a three-terminal device which consists of two high impedance inputs. One of the inputs is called the **Inverting Input**, marked with a negative or “minus” sign, (–). The other input is called the **Non-inverting Input**, marked with a positive or “plus” sign (+).

A third terminal represents the operational amplifiers output port which can both sink and source either a voltage or a current. In a linear operational amplifier, the output signal is the amplification factor, known as the amplifiers gain (A) multiplied by the value of the input signal and depending on the nature of these input and output signals, there can be four different classifications of operational amplifier gain.

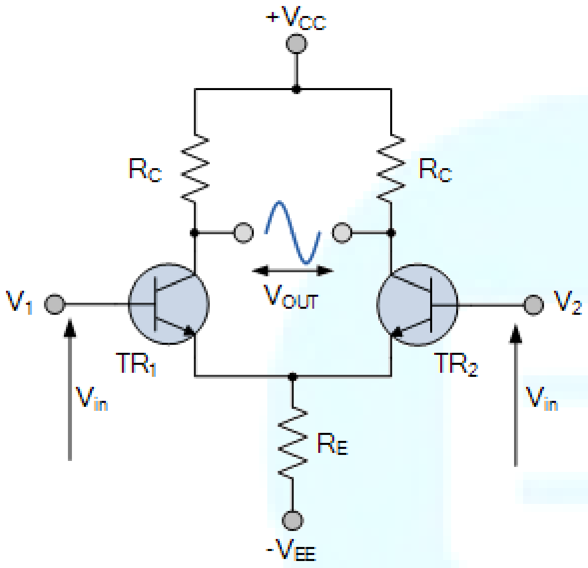
- Voltage – Voltage “in” and Voltage “out”
- Current – Current “in” and Current “out”
- Transconductance – Voltage “in” and Current “out”
- Transresistance – Current “in” and Voltage “out”

Since most of the circuits dealing with operational amplifiers are voltage amplifiers, we will limit the tutorials in this section to voltage amplifiers only, (Vin and Vout).

The output voltage signal from an Operational Amplifier is the difference between the signals being applied to its two individual inputs. In other words, an op-amps output signal is the difference between the two input signals as the input stage of an Operational Amplifier is in fact a differential amplifier as shown below.

Differential Amplifier

The circuit below shows a generalized form of a differential amplifier with two inputs marked V1 and V2. The two identical transistors TR1 and TR2 are both biased at the same operating point with their emitters connected together and returned to the common rail, -Vee by way of resistor Re.



The circuit operates from a dual supply +Vcc and -Vee which ensures a constant supply. The voltage that appears at the output, Vout of the amplifier is the difference between the two input signals as the two base inputs are in *anti-phase* with each other.

So as the forward bias of transistor, TR1 is increased, the forward bias of transistor TR2 is reduced and vice versa. Then if the two transistors are perfectly matched, the current flowing through the common emitter resistor, Re will remain constant.

Like the input signal, the output signal is also balanced and since the collector voltages either swing in opposite directions (anti-phase) or in the same direction (in-phase) the output voltage signal, taken from between the two collectors is, assuming a perfectly balanced circuit the zero difference between the two collector voltages.

This is known as *the Common Mode of Operation* with the **common mode gain** of the amplifier being the output gain when the input is zero.

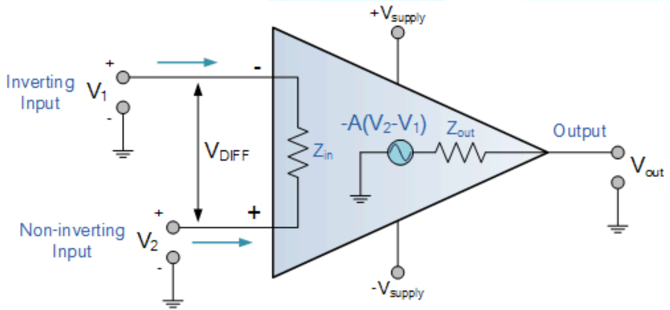
Operational Amplifiers also have one output (although there are ones with an additional differential output) of low impedance that is referenced to a common ground terminal and it should ignore any common mode signals that is, if an identical signal is applied to both the inverting and non-inverting inputs there should no change to the output.

However, in real amplifiers there is always some variation and the ratio of the change to the output voltage with regards to the change in the common mode input voltage is called the **Common Mode Rejection Ratio** or **CMRR** for short.

Operational Amplifiers on their own have a very high open loop DC gain and by applying some form of **Negative Feedback** we can produce an operational amplifier circuit that has a very precise gain characteristic that is dependant only on the feedback used. Note that the term "open loop" means that there are no feedback components used around the amplifier so the feedback path or loop is open.

An operational amplifier only responds to the difference between the voltages on its two input terminals, known commonly as the "*Differential Input Voltage*" and not to their common potential. Then if the same voltage potential is applied to both terminals the resultant output will be zero. An Operational Amplifiers gain is commonly known as the **Open Loop Differential Gain**, and is given the symbol (A_o).

Equivalent Circuit of an Ideal Operational Amplifier



Op-amp Parameter and Idealised Characteristic

Open Loop Gain, (Avo): Infinite – The main function of an operational amplifier is to amplify the input signal and the more open loop gain it has the better. Open-loop gain is the gain of the op-amp without positive or negative feedback and for such an amplifier the gain will be infinite but typical real values range from about 20,000 to 200,000.

Input impedance, (Z_{IN})

Infinite – Input impedance is the ratio of input voltage to input current and is assumed to be infinite to prevent any current flowing from the source supply into the amplifiers input circuitry (IIN = 0). Real op-amps have input leakage currents from a few pico-amps to a few milli-amps.

Output impedance, (Z_{OUT})

Zero – The output impedance of the ideal operational amplifier is assumed to be zero acting as a perfect internal voltage source with no internal resistance so that it can supply as much current as necessary to the load. This internal resistance is effectively in series with the load thereby reducing the output voltage available to the load. Real op-amps have output impedances in the 100-20kΩ range.

Bandwidth, (BW)

Infinite – An ideal operational amplifier has an infinite frequency response and can amplify any frequency signal from DC to the highest AC frequencies so it is therefore assumed to have an infinite bandwidth. With real op-amps, the bandwidth is limited by the Gain-Bandwidth product (GB), which is equal to the frequency where the amplifiers gain becomes unity.

Offset Voltage, (VIO)

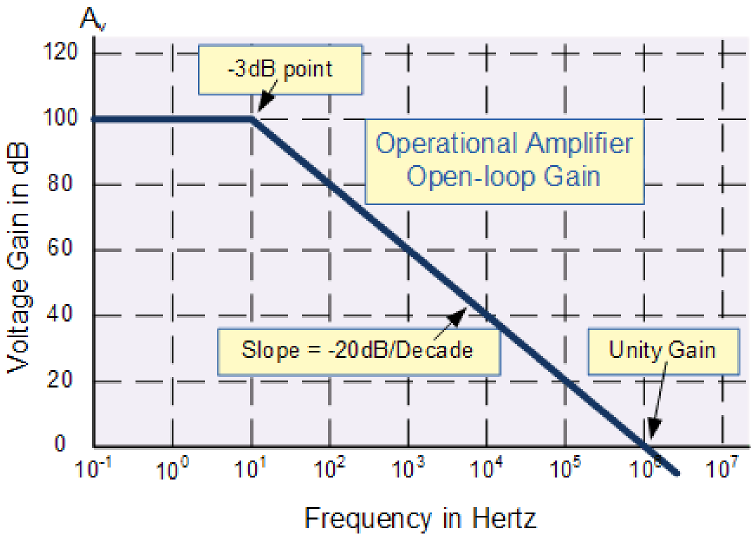
Zero – The amplifiers output will be zero when the voltage difference between the inverting and the non-inverting inputs is zero, the same or when both inputs are grounded. Real op-amps have some amount of output offset voltage.

From these “idealized” characteristics above, we can see that the input resistance is infinite, so **no current flows into either input terminal** (the “current rule”) and that the **differential input offset voltage is zero** (the “voltage rule”). It is important to remember these two properties as they will help us understand the workings of the **Operational Amplifier** with regards to the analysis and design of op-amp circuits.

However, real **Operational Amplifiers** such as the commonly available **uA741**, for example do not have infinite gain or bandwidth but have a typical “Open Loop Gain” which is defined as the amplifiers output amplification without any external feedback signals connected to it.

For a typical operational amplifier, this open loop gain can be as high as 100dB at DC (zero Hz). Generally, an op-amps output gain decreases linearly as frequency increases down to “Unity Gain” or 1, at about 1MHz. This effect is shown in the following open loop gain response curve.

Open-loop Frequency Response Curve



From this frequency response curve, we can see that the product of the gain against frequency is constant at any point along the curve. Also that the unity gain (0dB) frequency also determines the gain of the amplifier at any point along the curve. This constant is generally known as the **Gain Bandwidth Product** or **GBP**. Therefore:

GBP = Gain x Bandwidth = A x BW

For example, from the graph above the gain of the amplifier at 100kHz is given as 20dB or 10, then the gain bandwidth product is calculated as:

GBP = A x BW = 10 x 100,000Hz = 1,000,000.

Similarly, the operational amplifiers gain at 1kHz = 60dB or 1000, therefore the GBP is given as:

GBP = A x BW = 1,000 x 1,000Hz = 1,000,000.

The **Voltage Gain** (A_V) of the operational amplifier can be found using the following formula:

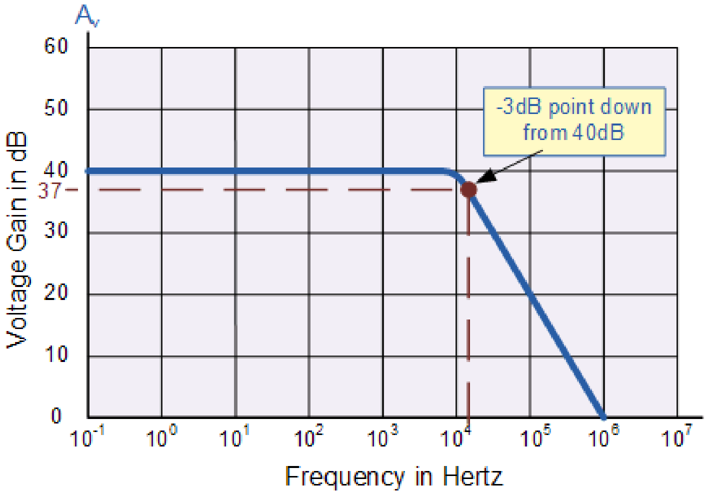
$$\textbf{Voltage Gain, (A)} = \frac{V_{out}}{V_{in}}$$

and in **Decibels** or (dB) is given as:

$$20\log(A) \ \text{or} \ 20\log\frac{V_{out}}{V_{in}} \ \textit{in dB}$$

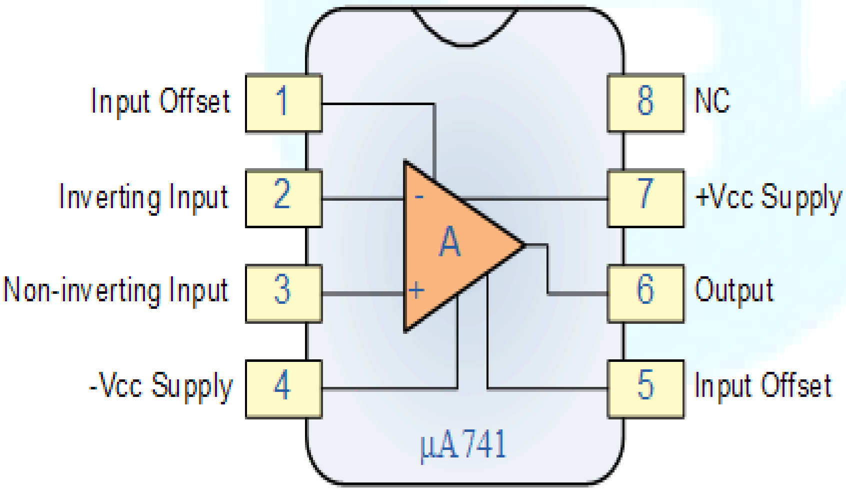
An Operational Amplifiers Bandwidth

The operational amplifiers bandwidth is the frequency range over which the voltage gain of the amplifier is above **70.7%** or **-3dB** (where 0dB is the maximum) of its maximum output value as shown below.



Here we have used the 40dB line as an example. The -3dB or 70.7% of Vmax down point from the frequency response curve is given as 37dB. Taking a line across until it intersects with the main GBP curve gives us a frequency point just above the 10kHz line at about 12 to 15kHz. We can now calculate this more accurately as we already know the GBP of the amplifier, in this particular case 1MHz.

Operational amplifiers are available in IC packages of either single, dual or quad op-amps within one single device. The most commonly available and used of all operational amplifiers in basic electronic kits and projects is the industry standard µA-741.



Inverting Operational Amplifier

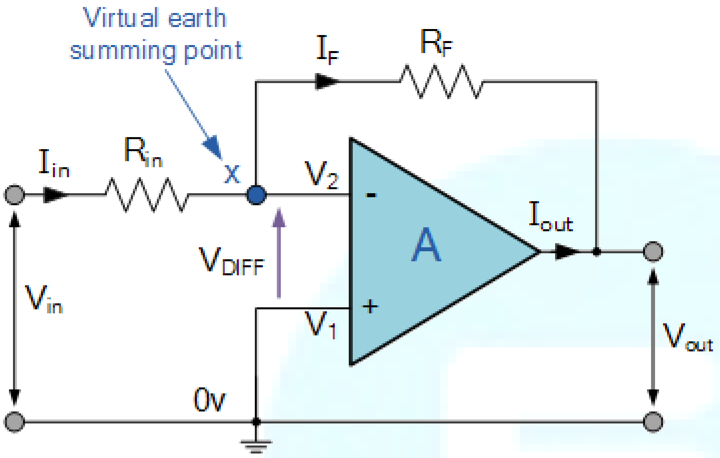
The Inverting Operational Amplifier configuration is one of the simplest and most commonly used op-amp topologies

Negative Feedback is the process of "feeding back" a fraction of the output signal back to the input, but to make the feedback negative, we must feed it back to the negative or "inverting input" terminal of the op-amp using an external **Feedback Resistor** called Rƒ. This feedback connection between the output and the inverting input terminal forces the differential input voltage towards zero.

This effect produces a closed loop circuit to the amplifier resulting in the gain of the amplifier now being called its **Closed-loop Gain**. Then a closed-loop inverting amplifier uses negative feedback to accurately control the overall gain of the amplifier, but at a cost in the reduction of the amplifiers gain.

This negative feedback results in the inverting input terminal having a different signal on it than the actual input voltage as it will be the sum of the input voltage plus the negative feedback voltage giving it the label or term of a *Summing Point*.

Inverting Operational Amplifier Configuration



In this **Inverting Amplifier** circuit, the operational amplifier is connected with feedback to produce a closed loop operation. When dealing with operational amplifiers there are two very important rules to remember about inverting amplifiers, these are: "No current flows into the input terminal" and that "V1 always equals V2". However, in real world op-amp circuits both of these rules are slightly broken.

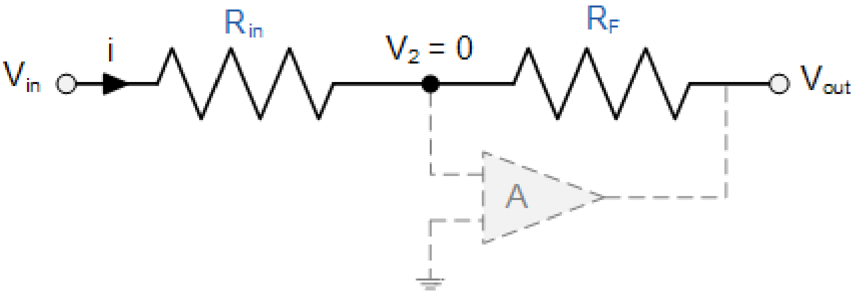
This is because the junction of the input and feedback signal (X) is at the same potential as the positive (+) input which is at zero volts or ground then, the junction is a **"Virtual Earth"**. Because of this virtual earth node, the input resistance of the amplifier is equal to the value of the input resistor, Rin and the closed loop gain of the inverting amplifier can be set by the ratio of the two external resistors.

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.

- No Current Flows into the Input Terminals
- 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.

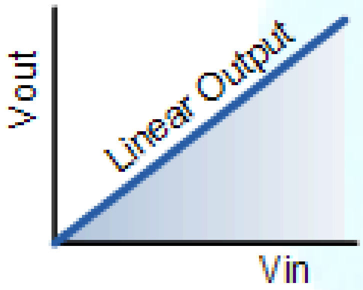


Closed-Loop Voltage Gain of an Inverting Amplifier is given as.

$$\text{Gain (Av)} = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}$$

Then Vout

$$\text{Vout} = -\frac{\text{Rf}}{\text{Rin}} \times \text{Vin}$$

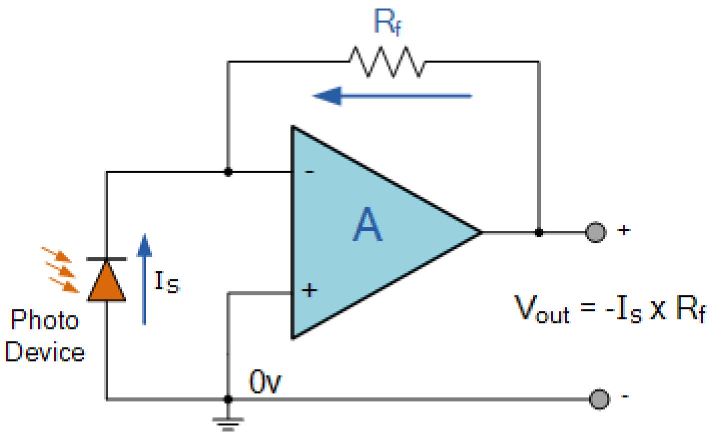


The negative sign in the equation indicates an inversion of the output signal with respect to the input as it is 180° out of phase. This is due to the feedback being negative in value.

The equation for the output voltage Vout also shows that the circuit is linear in nature for a fixed amplifier gain as Vout = Vin x Gain. This property can be very useful for converting a smaller sensor signal to a much larger voltage.

Another useful application of an inverting amplifier is that of a "transresistance amplifier" circuit. A **Transresistance Amplifier** also known as a "transimpedance amplifier", is basically a current-to-voltage converter (Current "in" and Voltage "out"). They can be used in low-power applications to convert a very small current generated by a photo-diode or photo-detecting device etc, into a usable output voltage which is proportional to the input current as shown.

Transresistance Amplifier Circuit



The simple light-activated circuit above, converts a current generated by the photo-diode into a voltage. The feedback resistor Rf sets the operating voltage point at the inverting input and controls the amount of output. The output voltage is given as Vout = Is x Rf. Therefore, the output voltage is proportional to the amount of input current generated by the photo-diode.

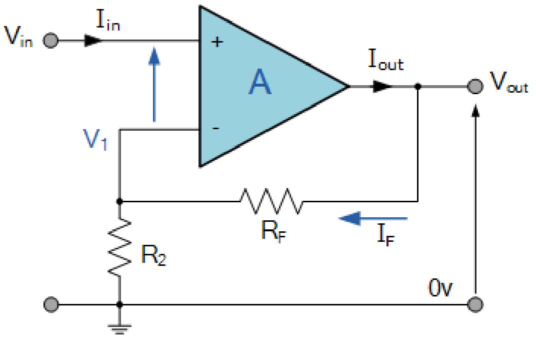
Non-inverting Operational Amplifier

The second basic configuration of an operational amplifier circuit is that of a Non-inverting **Operational Amplifier design.**

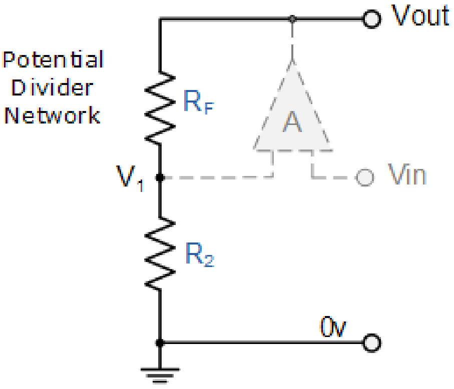
In this configuration, the input voltage signal, (V_{IN}) is applied directly to the non-inverting (+) input terminal which means that the output gain of the amplifier becomes "Positive" in value in contrast to the "Inverting Amplifier" circuit we saw in the last tutorial whose output gain is negative in value. The result of this is that the output signal is "in-phase" with the input signal.

Feedback control of the non-inverting operational amplifier is achieved by applying a small part of the output voltage signal back to the inverting (–) input terminal via a Rf – R2 voltage divider network, again producing negative feedback. This closed-loop configuration produces a non-inverting amplifier circuit with very good stability, a very high input impedance, Rin approaching infinity, as no current flows into the positive input terminal, (ideal conditions) and a low output impedance, Rout as shown below.

Non-inverting Operational Amplifier Configuration



Equivalent Potential Divider Network



Then using the formula to calculate the output voltage of a potential divider network, we can calculate the closed-loop voltage gain (AV) of the **Non-inverting Amplifier** as follows:

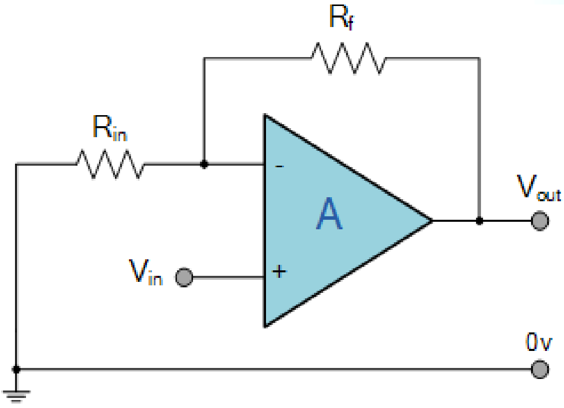
the closed loop voltage gain of a **Non-inverting Operational Amplifier** will be given as:

$$A_{(v)} = 1 + \frac{R_F}{R_2}$$

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 ratio 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, (A_O).

We can easily convert an inverting operational amplifier configuration into a non-inverting amplifier configuration by simply changing the input connections as shown.



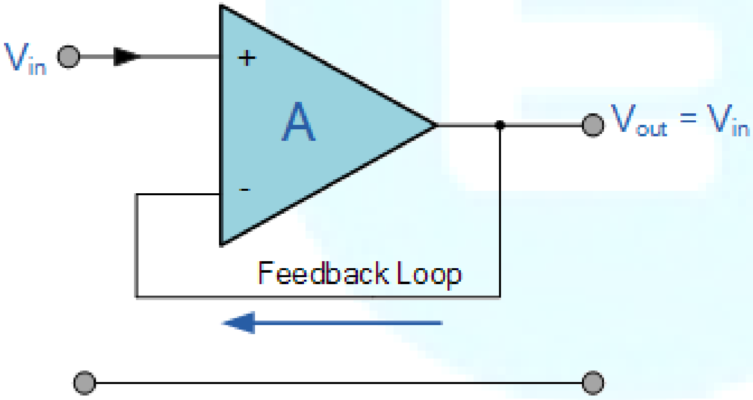
Voltage Follower (Unity Gain Buffer)

If we made the feedback resistor, Rƒ equal to zero, (Rƒ = 0), and resistor R2 equal to infinity, (R2 = ∞), then the resulting circuit would have a fixed gain of "1" (unity) as all the output voltage is fed back to the inverting input terminal (negative feedback). This configuration would produce a special type of the non-inverting amplifier circuit called a **Voltage Follower**, also known as a "unity gain buffer".

As the input signal is connected directly to the non-inverting input of the amplifier the output signal is not inverted resulting in the output voltage being equal to the input voltage, thus Vout = Vin. This then makes the **voltage follower** circuit ideal as a constant voltage source or voltage regulator because of its input to output isolation properties.

The advantage of the unity gain voltage follower configuration is that it can be used when impedance matching or circuit isolation is more important than voltage or current amplification as it maintains the input signal voltage at its output terminal. Also, the input impedance of the voltage follower circuit is extremely high, typically above 1MΩ as it is equal to that of the operational amplifiers input resistance times its gain (Rin x A_O). The op-amps output impedance is very low since an ideal op-amp condition is assumed so is unaffected by changes in load.

Non-inverting Voltage Follower



In this non-inverting circuit configuration, the input impedance Rin has increased to infinity and the feedback impedance Rƒ reduced to zero. The output is connected directly back to the negative inverting input so the feedback is 100% and Vin is exactly equal to Vout giving it a fixed gain of 1 or unity.

Since no current flows into the non-inverting input terminal the input impedance is infinite (ideal conditions) so zero current will flow through the feedback loop. Thus, any value of resistance may be placed in the feedback loop without affecting the characteristics of the circuit as no current flows through it so there is zero voltage drop across it resulting in zero power loss.

As the input impedance is extremely high, the unity gain buffer (voltage follower) can be used to provide a large power gain as the extra power comes from the op-amps supply rails and through the op-amps output to the load and not directly from the input.

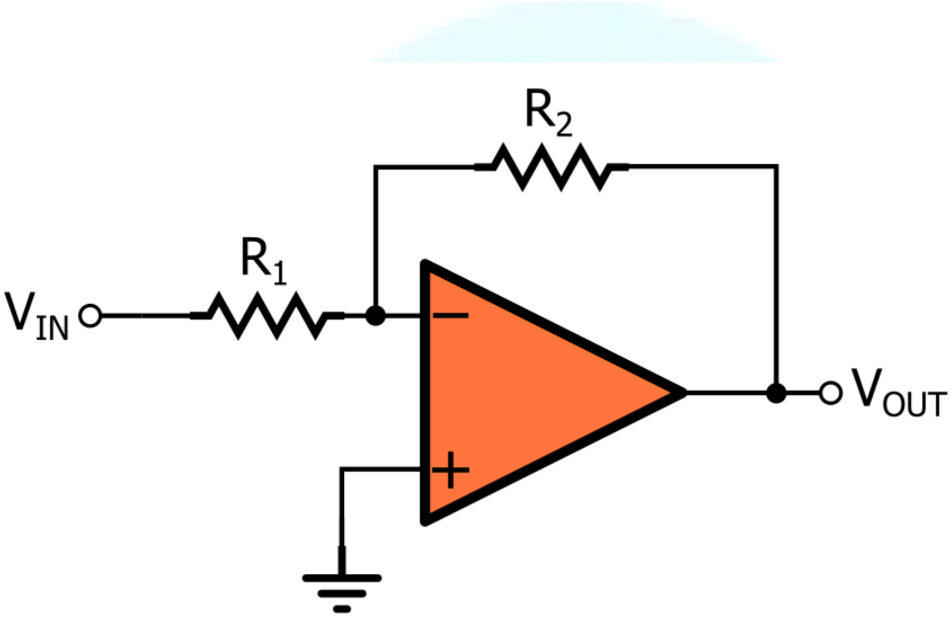
However, in most real unity gain buffer circuits there are leakage currents and parasitic capacitances present so a low value (typically 1kΩ) resistor is required in the feedback loop to help reduce the effects of these leakage currents providing stability especially if the operational amplifier is of a current feedback type.

Applications of Op Amp

A linear amplifier like an op amp has many different applications. It has a high open loop gain, high input impedance and low output impedance. It has high common mode rejection ratio. Due to these favourable characteristics, it is used for different application

Op Amp applications as Inverting Amplifiers

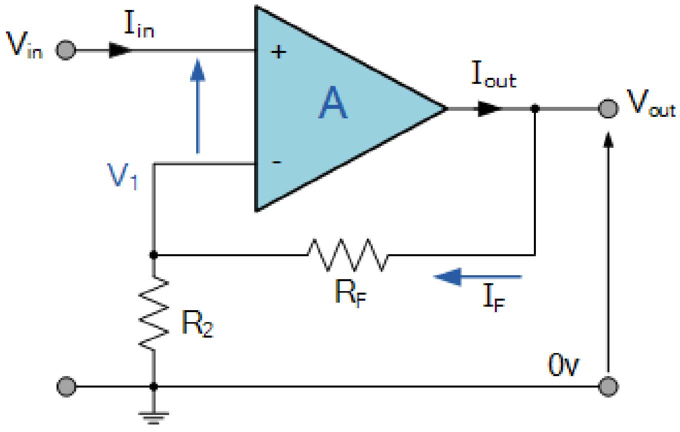
Op-Amp can be used as an inverting amplifier.



- The inverting circuits, implemented with an Op-Amp, are more constant, distortion is comparatively lower, provide a better transitory response.
- When Op-Amp is applied in a closed loop, there is a linear relationship between input and output.
- The inverting amplifier can be applied for unity gain if Rf = Ri (where, Rf is the feedback resistor and Ri is input resistor)

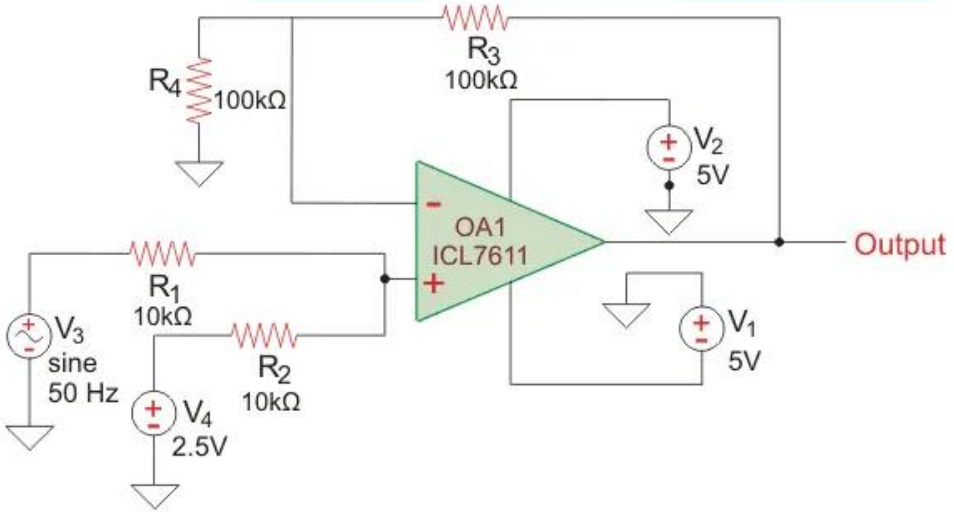
Op Amp Applications as Non-Inverting Amplifiers

The input signal when applied to the non-inverting input (+), the output is applied back to the input via the feedback circuit created by Rf and Ri (where, Rf is the feedback resistor and Ri is input resistance).



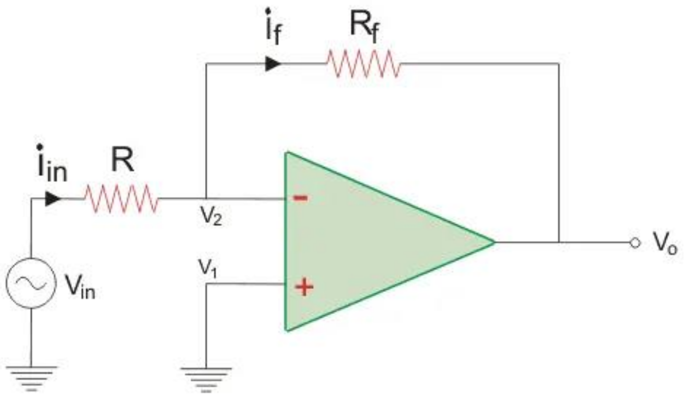
Op Amp application as a Phase Shifter

Op-Amp is used for direct coupling procedure and so DC voltage level at the emitter terminal increases from phase to phase. This rapidly increasing DC level is likely to shift the operating point of the upcoming stages. Thus, to move down the increasing voltage swing, this phase shifter is applied. The phase shifter performs by adding a DC voltage level to the output of fall stage to pass the output to a ground level.



Op Amp as Scale Changer

Op-Amp functions as a scale changer through small signals with constant-gain in both inverting and non-inverting amplifiers.

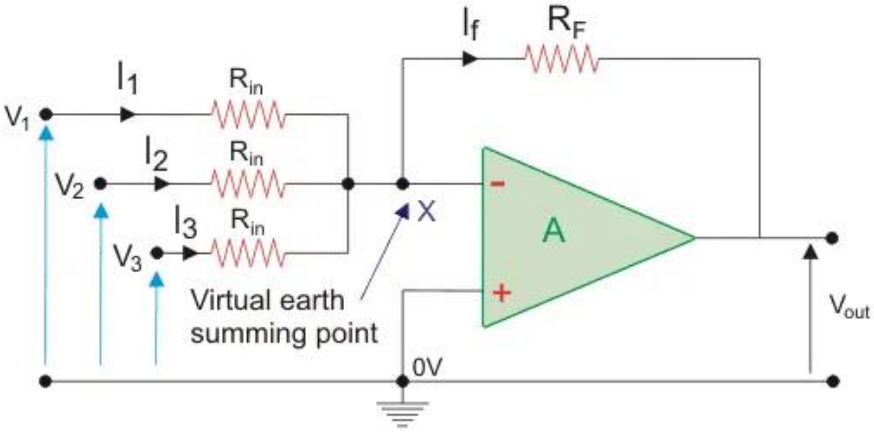


Non-inverting terminal is grounded whereas R1 links the input signal v1 to the inverting input. A feedback resistor Rf is then connected from output to the inverting input. The closed loop gain of the inverting amplifier works based on the ratio of the two external resistors R1 and Rf and Op-Amp acts as a negative scaler when it multiplies the input by a negative constant factor.

While in need for an output that is equal to input for getting multiplied by a positive constant the positive scaler circuit is used by applying negative feedback.

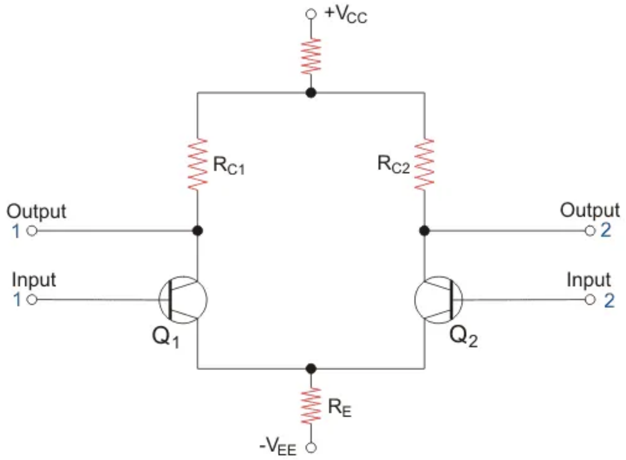
Op Amp Applications as Adder or Summing Amplifier

Op-amp can be used to sum the input voltage of two or more sources into a single output voltage. Below is a circuit diagram depicting the application of an op-amp as an adder or summing amplifier. The input voltages are applied to the inverting terminal of the op-amp. The inverting terminal is grounded. The output voltage is proportional to the sum of the input voltages.



Op Amp Applications as a Differential Amplifier

Differential Amplifier is a useful blend of both the inverting amplifier and non-inverting amplifier. It is mostly used to amplify the diversity amid two input signals.

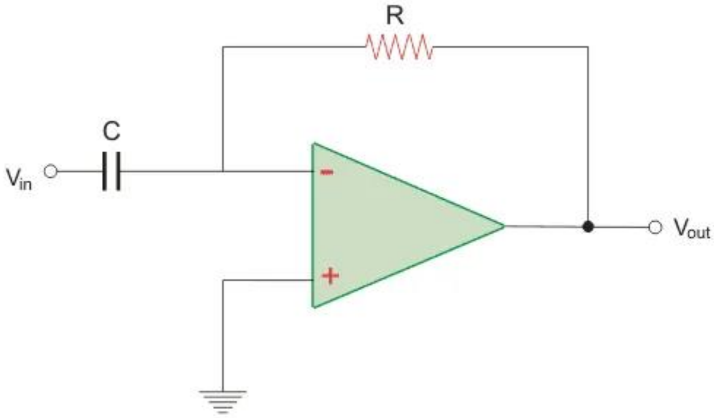


Major applications of Differential Amplifiers are

- Signal Amplification
- Input stage emitter coupled logic
- Switch
- Controlling of Motors and Servo Motors

Example: it is useful while eliminating the noise in ambience as through differential amplifier, you can eliminate the connected protected cable or twisted pair cable mostly used to eradicate the transitory noise.

Op Amp application as a Differentiator

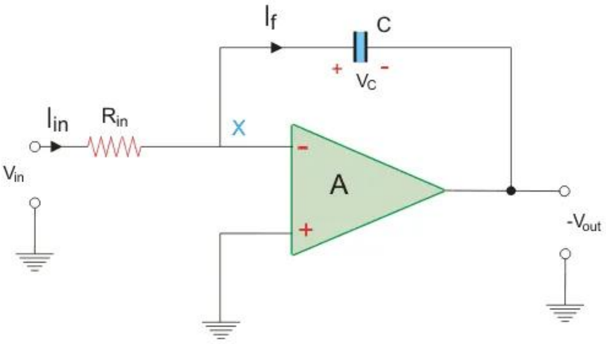


Op-amp can be used as a differentiator where the output is the first derivative of the input signal. The following equation gives the relation between the input signal and the output signal.

$$V_{OUT} = -R_F C \frac{dV_{IN}}{dt}$$

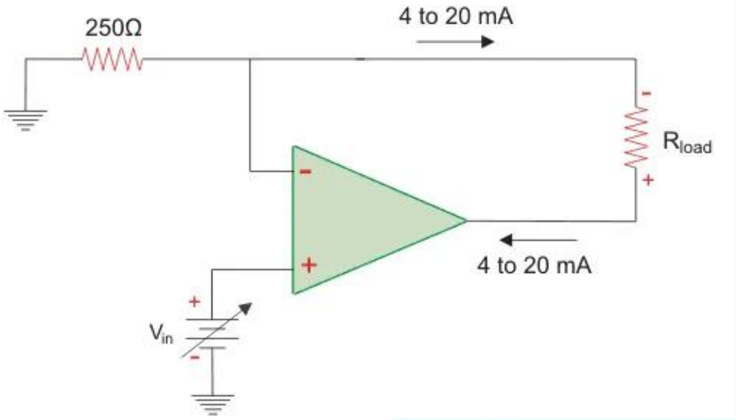
Op Amp Applications as Integrator

Op-amp is used as an integrator also. The integrator op-amp produces an output that is proportional to the amplitude of the input signal as well as the duration of the input signal. Instead of a resistor in the feedback loop, we have a capacitor. It is able to perform the mathematical operation of integration as the output varies with the input and duration of the signal.



Op Amp Applications as Voltage to Current Converter

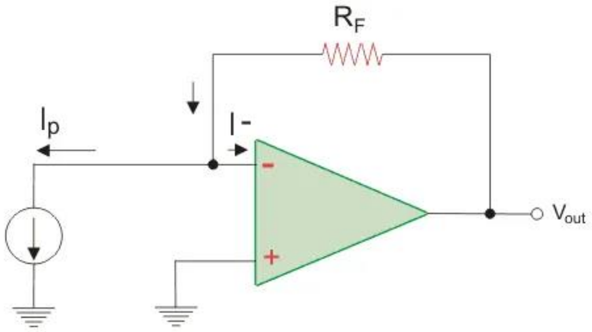
An op-amp with negative feedback is generally used for voltage to current conversions. Below you can see the circuit diagram. We are not going into the details here, just we will discuss the circuit given below. The voltage is applied to the non-inverting terminal and the output is feedback to the inverting terminal. It is also grounded using a resistor.



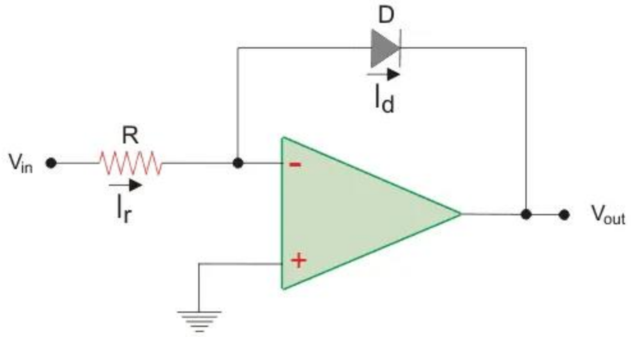
Op Amp Applications as Current to Voltage Converter

Op-amp can be used as a current to voltage converter using a very simple circuit as shown above. All we need is a feedback resistance connected to the output of the op-amp. The current source is fed into the inverting terminal and the non-inverting terminal is grounded. Here the output voltage is proportional to the input current. As an ideal op-amp has infinite resistance, the current cannot flow through the op-amp. The current flows through the feedback resistance and the voltage across it depends on the current source.

Vout =-Rf Iin



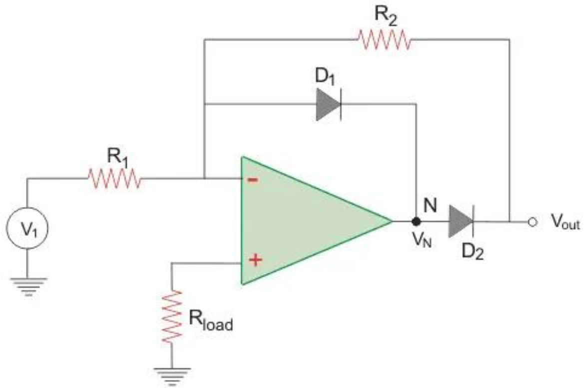
Op Amp Applications as Logarithmic Amplifier



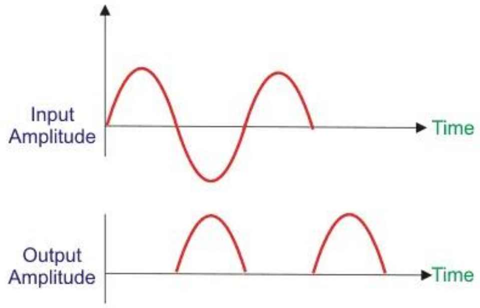
The logarithmic amplifier using op-amp is made by using a diode instead of a resistance in the feedback loop. The non-inverting terminal is grounded and the input voltage is fed to the inverting terminal. The output voltage is proportional to the logarithm of the input voltage and hence can be used as a logarithmic amplifier.

$$V_{out} = \frac{KT}{Q} \times I_n \left(\frac{V_{in}}{I_r} \times R \right)$$

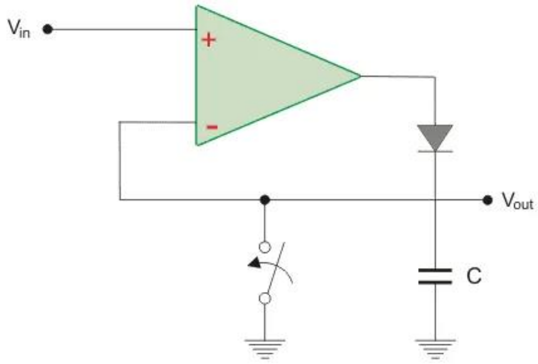
Op Amp Applications as Half Wave Rectifier



The circuit diagram above shows the usage of an op-amp as a half wave rectifier. During the positive cycle of voltage, diode D2 is reversed biased as the positive signal is inverted by the op-amp. So there will be no output. However, during the negative cycle of the input voltage, the diode D2 is forward biased and conducts. Therefore, the above circuit works as a half wave rectifier.



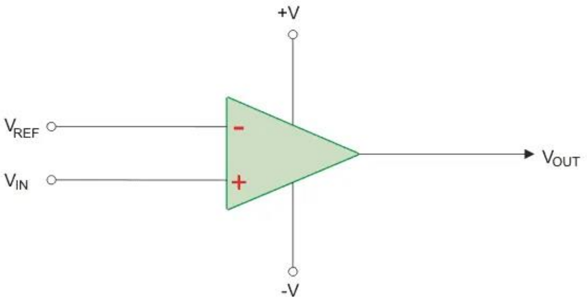
Op Amp Applications as Peak Detector



The circuit above shows the use of op-amp as a peak detector. The circuit uses a diode and a capacitor. When Vout is more than Vin, the output is positive and the diode conducts. Whereas when Vout is less than Vin, the diode is reversed biased and does not conduct. The capacitor charges to the most positive value.

Op-Amp as Voltage Comparator

The following figure shows block diagram of a voltage comparator



This is perhaps the easiest to comprehend. Two voltage sources are applied to the two terminals of the op-amp. Let the reference voltage be applied to the inverting terminal and the voltage to be measured is applied to the non-inverting terminal. If the voltage applied is greater than the reference voltage, we will get a positive output, else we will get a negative output.