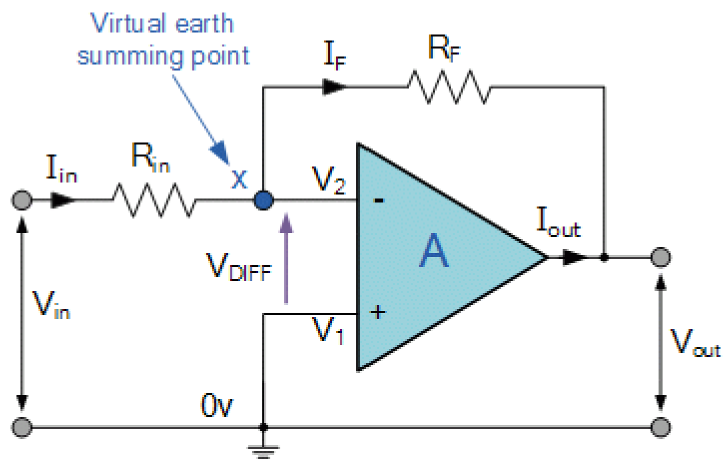


Inverting Operational Amplifier

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

We saw in the last tutorial that the **Open Loop Gain**, (A_{VO}) of an operational amplifier can be very high, as much as 1,000,000 (120dB) or more.

However, this very high gain is of no real use to us as it makes the amplifier both unstable and hard to control as the smallest of input signals, just a few micro-volts, (μV) would be enough to cause the output voltage to saturate and swing towards one or the other of the voltage supply rails losing complete control of the output.

As the open loop DC gain of an operational amplifier is extremely high we can therefore afford to lose some of this high gain by connecting a suitable resistor across the amplifier from the output terminal back to the inverting input terminal to both reduce and control the overall gain of the amplifier. This then produces and effect known commonly as Negative Feedback, and thus produces a very stable Operational Amplifier based system.

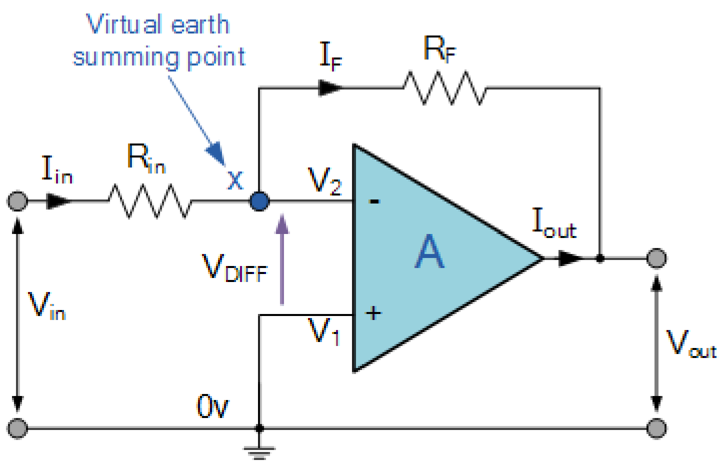
Negative Feedback is the process of "feeding back" a fraction of the output signal back to the input, but to make the feedback negative, we must feed it back to the negative or "inverting input" terminal of the op-amp using an external **Feedback Resistor** called $Rƒ$. This feedback connection between 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*. We must therefore separate the real input signal from the inverting input by using an **Input Resistor**, Rin.

As we are not using the positive non-inverting input this is connected to a common ground or zero voltage terminal as shown below, but the effect of this closed loop feedback circuit results in the voltage potential at the inverting input being equal to that at the non-inverting input producing a *Virtual Earth* summing point because it will be at the same potential as the grounded reference input. In other words, the op-amp becomes a "differential amplifier".

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.

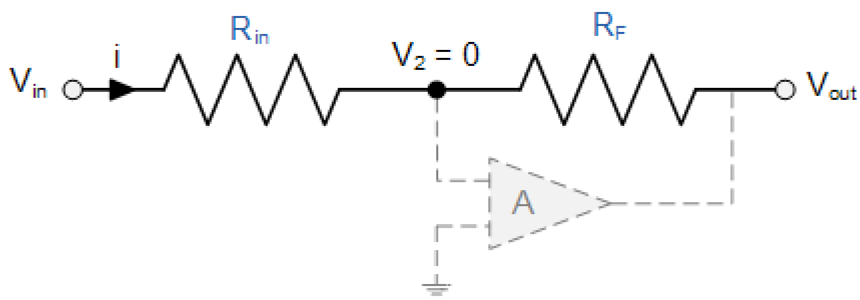
This is because the junction of the input and feedback signal (X) is at the same potential as the positive (+) input which is at zero volts or ground then, the junction is a **"Virtual Earth"**. Because of this virtual earth node the input resistance of the amplifier is equal to the value of the input 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.



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

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

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

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

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

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

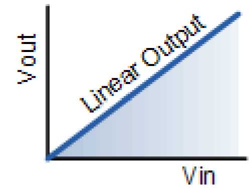
Then, the **Closed-Loop Voltage Gain** of an Inverting Amplifier is given as.

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

and this can be transposed to give Vout as:

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

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.

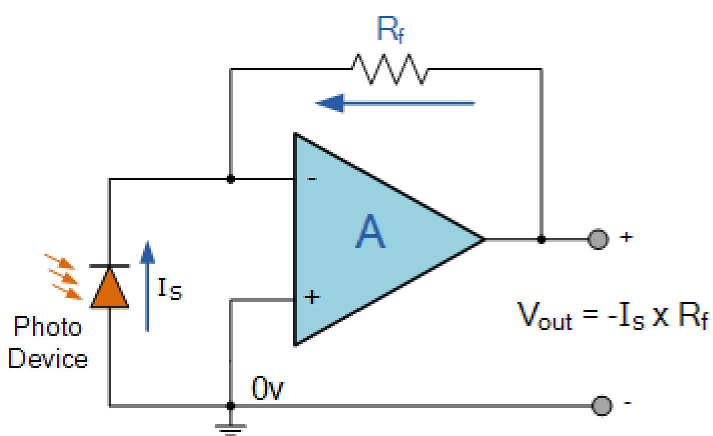


Linear Output

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.

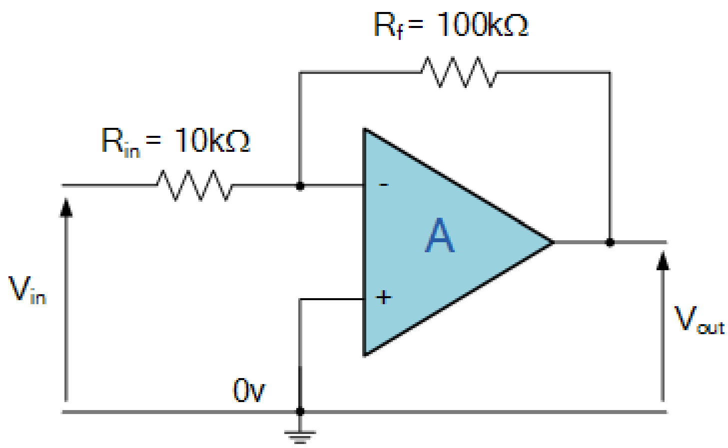
Transresistance Amplifier Circuit



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 = I_s x Rf. Therefore, the output voltage is proportional to the amount of input current generated by the photo-diode.

Inverting Op-amp Example No1

Find the closed loop gain of the following inverting amplifier circuit.



Using the previously found formula for the gain of the circuit

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

we can now substitute the values of the resistors in the circuit as follows,

Rin = 10kΩ and Rf = 100kΩ

and the gain of the circuit is calculated as: -Rf/Rin = 100k/10k = -10

Therefore, the closed loop gain of the inverting amplifier circuit above is given **-10** or **20dB**(20log(10)).

Inverting Op-amp Example No2

The gain of the original circuit is to be increased to **40** (32dB), find the new values of the resistors required.

Assuming that the input resistor is to remain at the same value of 10KΩ, then by re-arranging the closed loop voltage gain formula we can find the new value required for the feedback resistor Rf.

Gain = Rf/Rin

therefore, Rf = Gain x Rin

Rf = 40 x 10,000

Rf = 400,000 or 400KΩ

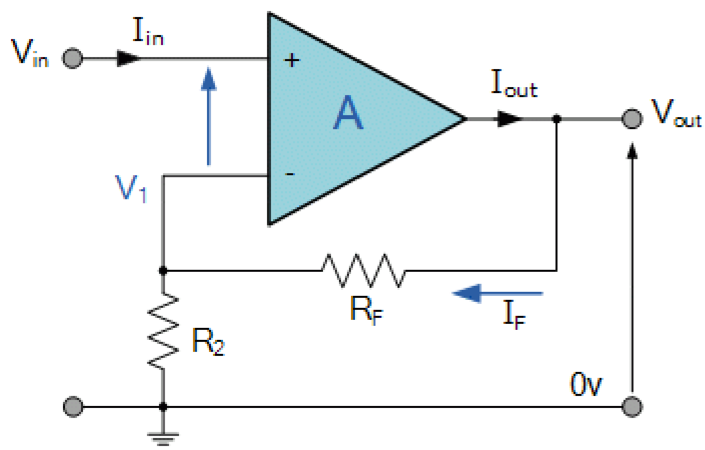
The new values of resistors required for the circuit to have a gain of **40** would be:

Rin = 10KΩ and Rf = 400KΩ

The formula could also be rearranged to give a new value of Rin, keeping the same value of Rf.

One final point to note about the **Inverting Amplifier** configuration for an operational amplifier, if the two resistors are of equal value, $R_{in} = R_f$ then the gain of the amplifier will be **-1** producing a complementary form of the input voltage at its output as $V_{out} = -V_{in}$. This type of inverting amplifier configuration is generally called a **Unity Gain Inverter** of simply an *Inverting Buffer*.

In the next tutorial about Operational Amplifiers, we will analyse the complement of the **Inverting Amplifier** operational amplifier circuit called the Non-inverting Amplifier that produces an output signal which is “in-phase” with the input.



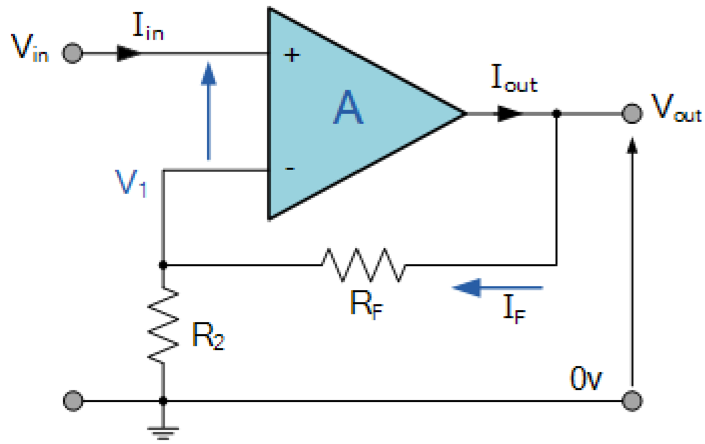
Non-inverting Operational Amplifier

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 $Rƒ - R2$ 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.

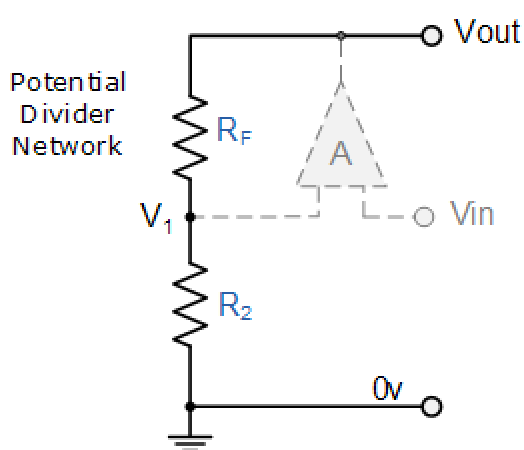
Non-inverting Operational Amplifier Configuration



In the previous Inverting Amplifier tutorial, we said that for an ideal op-amp "No current flows into the input terminal" of the amplifier and that "V1 always equals V2". This was because the junction of the input and feedback signal ($V1$) are at the same potential.

In other words the junction is a "virtual earth" summing point. Because of this virtual earth node the resistors, Rf and $R2$ form a simple potential divider network across the non-inverting amplifier with the voltage gain of the circuit being determined by the ratios of $R2$ and Rf as shown below.

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 (A_V) of the **Non-inverting Amplifier** as follows:

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

$$\text{Ideal Summing Point:} \quad V_1 = V_{IN}$$

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

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

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

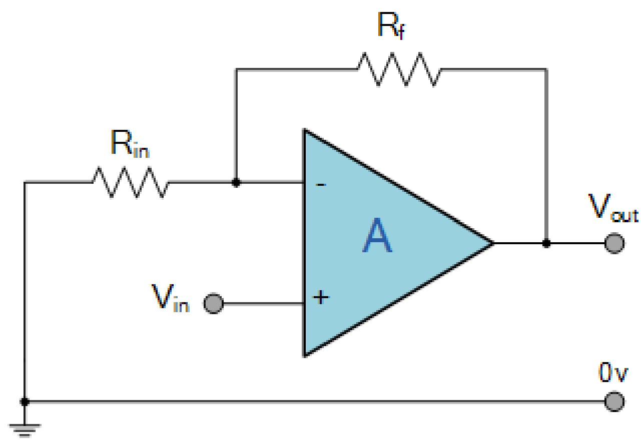
Then the closed loop voltage gain of a **Non-inverting Operational Amplifier** will be given as:

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

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.



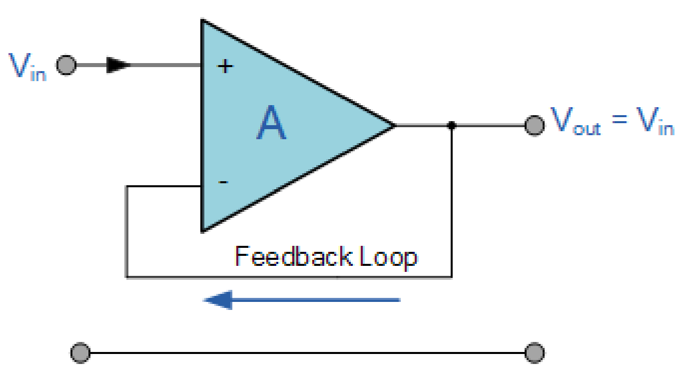
Voltage Follower (Unity Gain Buffer)

If we made the feedback resistor, Rf equal to zero, ($Rf = 0$), and resistor $R2$ equal to infinity, ($R2 = \infty$), then the circuit would have a fixed gain of "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".

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, $Vout = Vin$. This then makes the **voltage follower** circuit ideal as a Unity Gain Buffer circuit because of its isolation properties.

The advantage of the unity gain voltage follower is that it can be used when impedance matching or circuit isolation is more important than amplification as it maintains the signal voltage. The input impedance of the voltage follower circuit is very high, typically above 1MΩ as it is equal to that of the operational amplifiers input resistance times its gain ($Rin \times A_O$). Also its output impedance is very low since an ideal op-amp condition is assumed.

Non-inverting Voltage Follower



In this non-inverting circuit configuration, the input impedance Rin has increased to infinity and the feedback impedance Rf 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. As the input voltage Vin is applied to the non-inverting input the gain of the amplifier is given as:

$$V_{out} = A(V_{in})$$

$$(V_{in} = V+) \text{ and } (V_{out} = V-)$$

$$\text{therefore Gain, } (A_V) = \frac{V_{out}}{V_{in}} = +1$$

Since no current flows into the non-inverting input terminal the input impedance is infinite (ideal op-amp) and also no current flows through the feedback loop so any value of resistance may be placed in the feedback loop without affecting the characteristics of the circuit as no voltage is dissipated across it, zero current flows, zero voltage drop, zero power loss.

As the input current is zero giving zero input power, the voltage follower can provide a large power gain. However in most real unity gain buffer circuits a low value (typically 1kΩ) resistor is required to reduce any offset input leakage currents, and also if the operational amplifier is of a current feedback type.

The voltage follower or unity gain buffer is a special and very useful type of **Non-inverting amplifier**circuit that is commonly used in electronics to isolated circuits from each other especially in High-order state variable or Sallen-Key type active filters to separate one filter stage from the other. Typical digital buffer IC's available are the 74LS125 Quad 3-state buffer or the more common 74LS244 Octal buffer.

One final thought, the closed loop voltage gain of a voltage follower circuit is "1" or **Unity**. The open loop voltage gain of an operational amplifier with no feedback is **Infinite**. Then by carefully selecting the feedback components we can control the amount of gain produced by a non-inverting operational amplifier anywhere from one to infinity.

Thus far we have analysed an inverting and non-inverting amplifier circuit that has just one input signal, Vin. In the next tutorial about Operational Amplifiers, we will examine the effect of the output voltage, Vout by connecting more inputs to the amplifier. This then produces another common type of operational amplifier circuit called a Summing Amplifier which can be used to "add" together the voltages present on its inputs.