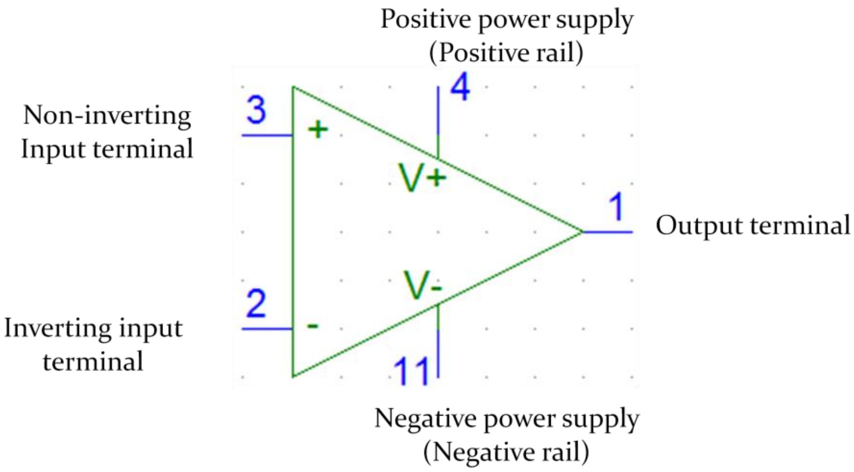
An **Operational Amplifier**, or op-amp for short, is fundamentally a voltage amplifying device designed to be used with external feedback components such as resistors. Without the amplification op-amp can also perform mathematical operations such as addition, subtraction, multiplication, division, differentiation and integration.

Op-amp has eight pins and five pins among them are very important. The circuit symbol for an op-amp is a triangle with five pins shown below.



An op-amp has a wide range of uses and depending how each pin is connected, the resulting circuit can be some of the following:

1. Voltage follower/ Source follower
2. Comparator
3. Inverting Amplifier
4. Non inverting Amplifier
5. Differential Amplifier
6. Summing Amplifier
7. Differentiator
8. Integrator
9. Filter
10. Analog to Digital Converter

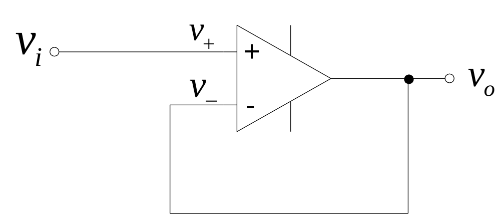
Ideal Vs Practical Op-amp

	Ideal Op-Amp	**Typical Op-Amp**
Input Resistance	infinity	$10^6\,\Omega$ - $10^{12}\,\Omega$
Input Current	0	10^{-12} – 10^{-8} A
Output Resistance	0	100 – 1000 Ω
Operational Gain	infinity	10^5 - 10^9
Common Mode Gain	0	10^{-5}
Bandwidth	infinity	Attenuates and phases at high frequencies (depends on slew rate)
Temperature	independent	Bandwidth and gain

Application circuits

Unity-Gain Buffer or voltage follower circuit

Voltage followers are used to boost the current available from a circuit without increasing the voltage at the same time.
The circuit can be used as a buffer or driver. This isolates the output circuit so the input is not affected in any way by the output device.
Voltage gain



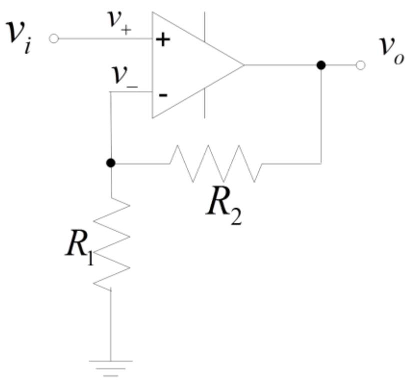
We know, the gain is nothing but the ratio between output and input voltage.

$$A_F = \frac{v_o}{v_i}$$

$v_i = v_+ = v_- = v_o$ [Op-amp tries to keep the voltage same in both input terminals ($v_+ = v_-$)]

$$A_F = \frac{v_o}{v_i} = 1$$

Non-inverting Amplifier



Closed-loop voltage gain

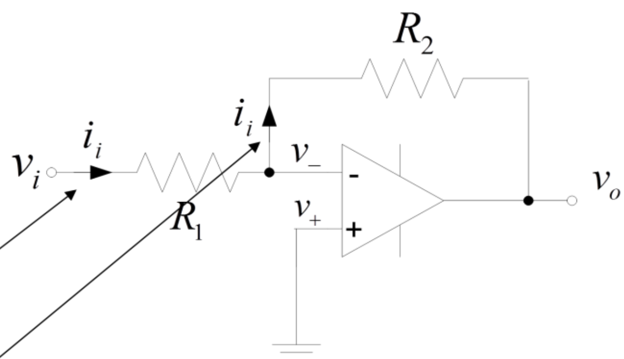
$$A_F = \frac{v_o}{v_i}$$

$$v_i = v_+ = v_- = \frac{R_1}{R_1 + R_2} v_o$$

$$A_F = \frac{v_o}{v_i} = 1 + \frac{R_2}{R_1}$$

Inverting Amplifier

Current into op amp is zero



$$v_- = v_+ = 0$$

$$i_i = \frac{v_i - 0}{R_1} = \frac{v_i}{R_1}$$

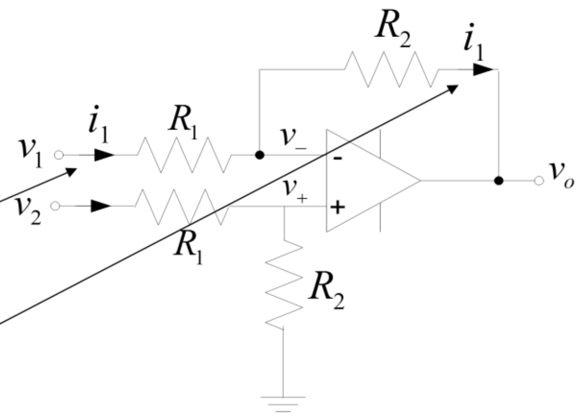
$$i_i = \frac{0 - v_0}{R_2} = \frac{-v_0}{R_2}$$

$$\frac{v_i}{R_1} = \frac{-v_0}{R_2}$$

$$A_F = \frac{v_o}{v_i} = -\frac{R_2}{R_1}$$

Differential Amplifier

Current into op amp is zero



$$v_- = v_+$$

$$i_1 = \frac{v_1 - v_-}{R_1}$$

$$i_1 = \frac{v_- - v_0}{R_2}$$

$$v_+ = \frac{R_2}{R_1 + R_2} v_2$$

$$\frac{v_1 - v_+}{R_1} = \frac{v_+ - v_0}{R_2}$$

$$\frac{v_1 - \frac{R_2}{R_1 + R_2} v_2}{R_1} = \frac{\frac{R_2}{R_1 + R_2} v_2 - v_0}{R_2}$$

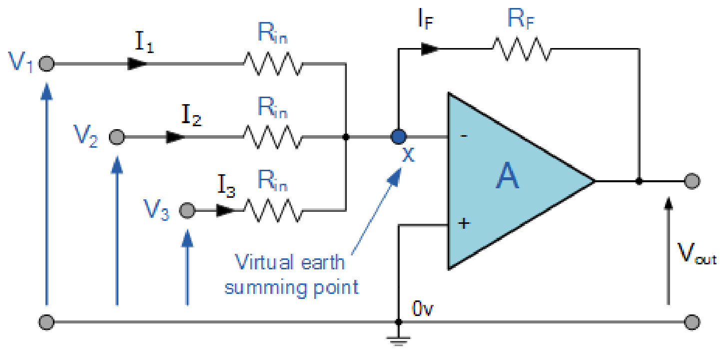
$$\frac{v_1 - \frac{R_2}{R_1 + R_2} v_2}{R_1} = \frac{\frac{R_2}{R_1 + R_2} v_2 - v_0}{R_2}$$

$$v_0 = -\frac{R_2}{R_1} v_1 + \frac{R_2}{R_1 + R_2} v_2 + \frac{R_2^2}{R_1 \left(R_1 + R_2\right)} v_2$$

$$v_0 = -\frac{R_2}{R_1} v_1 + \frac{R_2}{R_1 + R_2} \left(1 + \frac{R_2}{R_1}\right) v_2$$

$$v_0 = \frac{R_2}{R_1} \left(v_2 - v_1\right)$$

Summing Amplifier Circuit



In this simple summing amplifier circuit, the output voltage, (Vout) now becomes proportional to the sum of the input voltages, V1, V2, V3, etc. Then we can modify the original equation for the inverting amplifier to take account of these new inputs thus:

$$I_F = I_1 + I_2 + I_3 = -\left[\frac{V1}{Rin} + \frac{V2}{Rin} + \frac{V3}{Rin}\right]$$

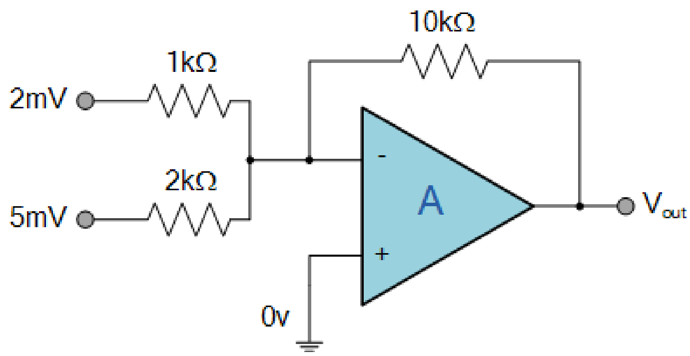
$$\text{Inverting Equation:}\ Vout = -\frac{Rf}{Rin} \times Vin$$

$$\text{then,}\ -Vout = \left[\frac{R_F}{Rin}V1 + \frac{R_F}{Rin}V2 + \frac{R_F}{Rin}V3\right]$$

$$V_{\mathrm{out}} = -R_{\mathrm{f}}\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots + \frac{V_n}{R_n}\right)$$

Find the output voltage of the following *Summing Amplifier* circuit.

Summing Amplifier



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,

$$A_1 = \frac{10k\Omega}{1k\Omega} = -10$$

$$A_2 = \frac{10k\Omega}{2k\Omega} = -5$$

We know that the output voltage is the sum of the two amplified input signals and is calculated as:

$$Vout = \left(A_1 \times V_1\right) + \left(A_2 \times V_2\right)$$

$$Vout = (-10(2mV)) + (-5(5mV)) = -45mV$$

Then the output voltage of the **Summing Amplifier** circuit above is given as **-45 mV** and is negative as its an inverting amplifier.

Op-amp low pass filter

The main disadvantage of passive filters is that the amplitude of the output signal is less than that of the input signal, ie, the gain is never greater than unity and that the load impedance affects the filters characteristics.

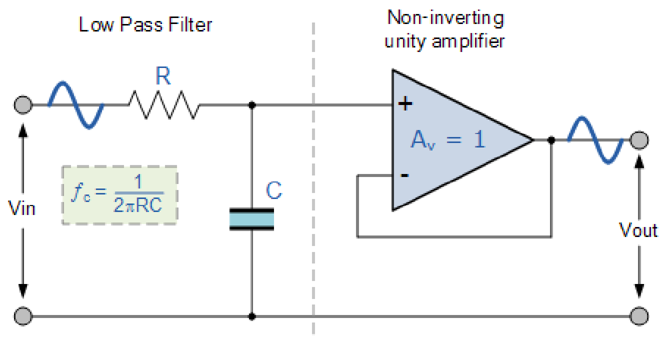
With passive filter circuits containing multiple stages, this loss in signal amplitude called “Attenuation” can become quiet severe. One way of restoring or controlling this loss of signal is by using amplification through the use of **Active Filters**.

As their name implies, **Active Filters** contain active components such as operational amplifiers, transistors or FET's within their circuit design. They draw their power from an external power source and use it to boost or amplify the output signal.

Filter amplification can also be used to either shape or alter the frequency response of the filter circuit by producing a more selective output response, making the output bandwidth of the filter more narrower or even wider. Then the main difference between a "passive filter" and an "active filter" is amplification.

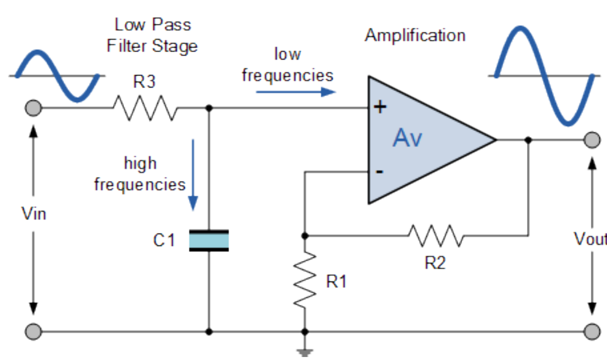
An active filter generally uses an operational amplifier (op-amp) within its design and in the Operational Amplifier tutorial we saw that an Op-amp has a high input impedance, a low output impedance and a voltage gain determined by the resistor network within its feedback loop.

Active Low Pass Filter



This first-order low pass active filter, consists simply of a passive RC filter stage providing a low frequency path to the input of a non-inverting operational amplifier. The amplifier is configured as a voltage-follower (Buffer) giving it a DC gain of one, Av = +1 or unity gain as opposed to the previous passive RC filter which has a DC gain of less than unity.

Active Low Pass Filter with Amplification



. For a non-inverting amplifier circuit, the magnitude of the voltage gain for the filter is given as a function of the feedback resistor (R_2) divided by its corresponding input resistor (R_1) value and is given as:

$$\text{DC gain} = \left(1 + \frac{R_2}{R_1}\right)$$

Therefore, the gain of an active low pass filter as a function of frequency will be:

Gain of a first-order low pass filter

$$\text{Voltage Gain, } (Av) = \frac{Vout}{Vin} = \frac{A_F}{\sqrt{1 + \left(\frac{f}{fc}\right)^2}}$$

Where:

- A_F = the pass band gain of the filter, (1 + R2/R1)
- f = the frequency of the input signal in Hertz, (Hz)
- fc = the cut-off frequency in Hertz, (Hz)

Thus, the **Active Low Pass Filter** has a constant gain A_F from 0Hz to the high frequency cut-off point, f_C. At f_C the gain is $0.707A_F$, and after f_C it decreases at a constant rate as the frequency increases. That is, when the frequency is increased tenfold (one decade), the voltage gain is divided by 10.

Active Low Pass Filter Example

Design a non-inverting active low pass filter circuit that has a gain of ten at low frequencies, a high frequency cut-off or corner frequency of 159Hz and an input impedance of 10KΩ.

The voltage gain of a non-inverting operational amplifier is given as:

$$A_F = 1 + \frac{R_2}{R_1} = 10$$

Assume a value for resistor R1 of 1kΩ rearranging the formula above gives a value for R2of

$$R_2 = (10 - 1)\ x\ R_1 = 9\ x\ 1k\Omega = 9k\Omega$$

then, for a voltage gain of 10, R1 = 1kΩ and R2 = 9kΩ. However, a 9kΩ resistor does not exist so the next preferred value of 9k1Ω is used instead.

The cut-off or corner frequency (fc) is given as being 159Hz with an input impedance of 10kΩ. This cut-off frequency can be found by using the formula:

$fc = \frac{1}{2\pi RC} Hz$ Where, f_c = 159Hz and R = 10kΩ.

then, by rearranging the above formula we can find the value for capacitor C as:

$$C = \frac{1}{2\pi\, fc\, R} = \frac{1}{2\pi\ x\ 159\ x\ 10k\Omega} = 100nF$$

Then the final circuit along with its frequency response is given below as: