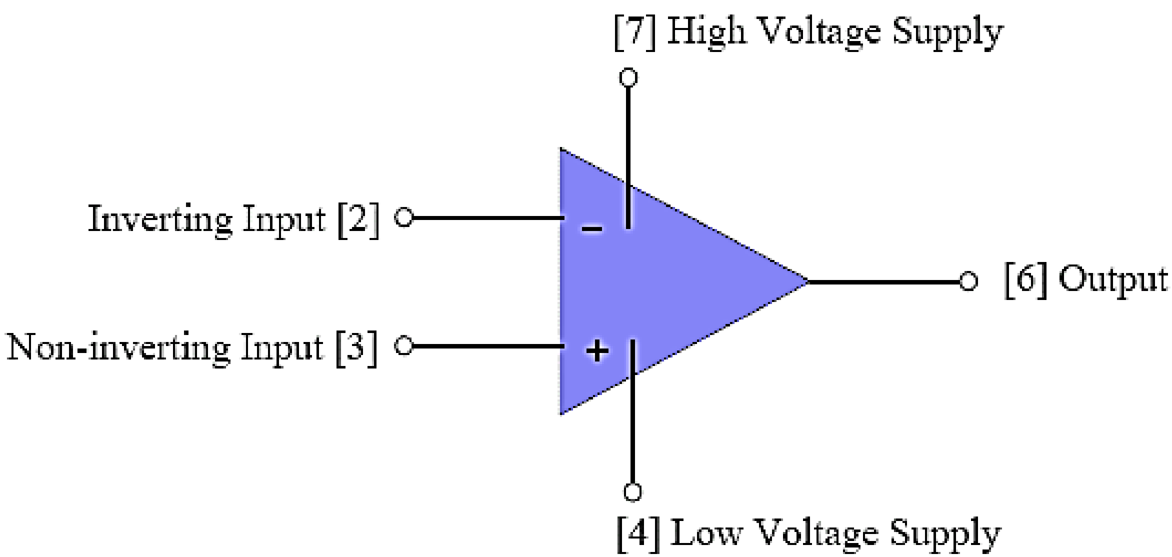
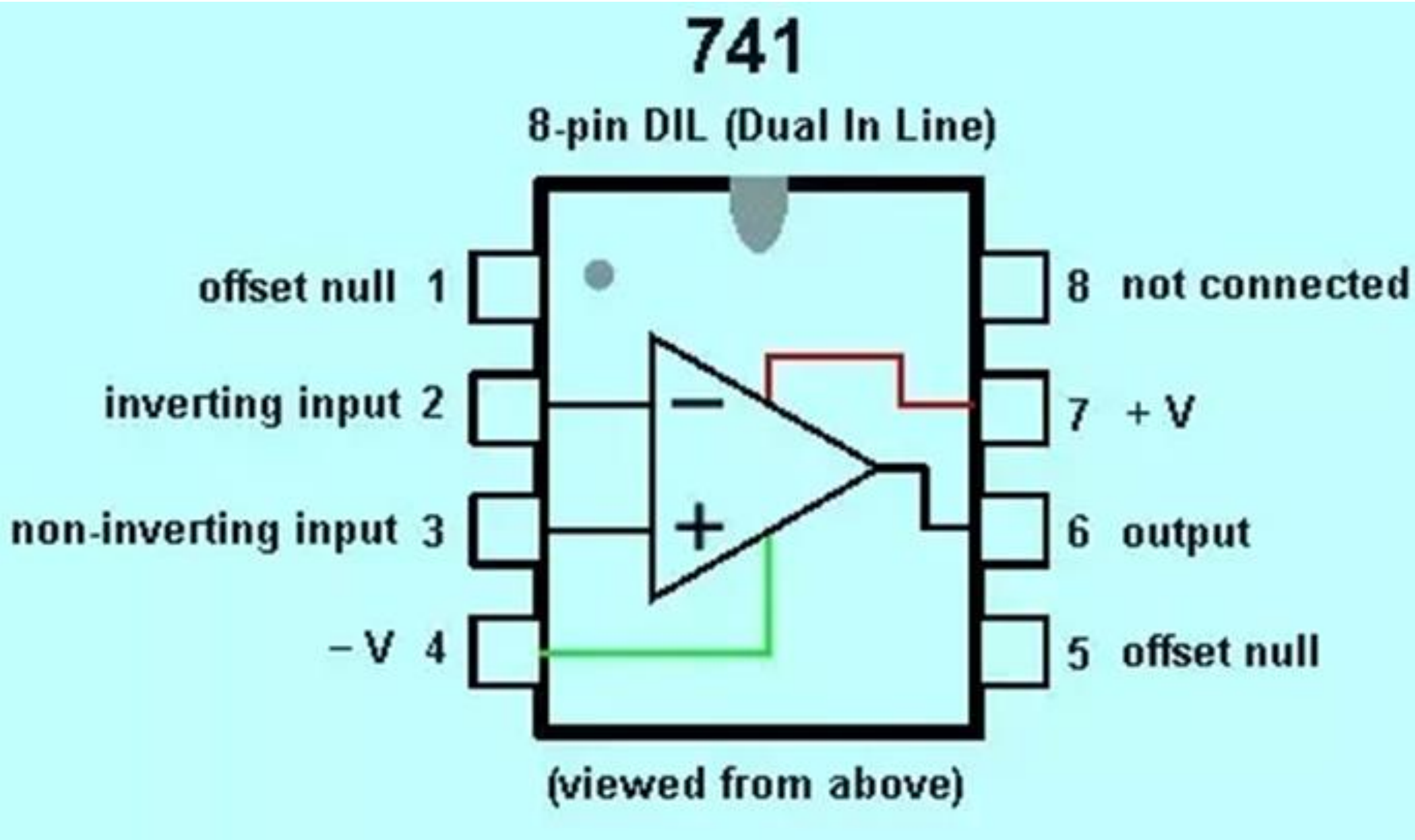
Introduction

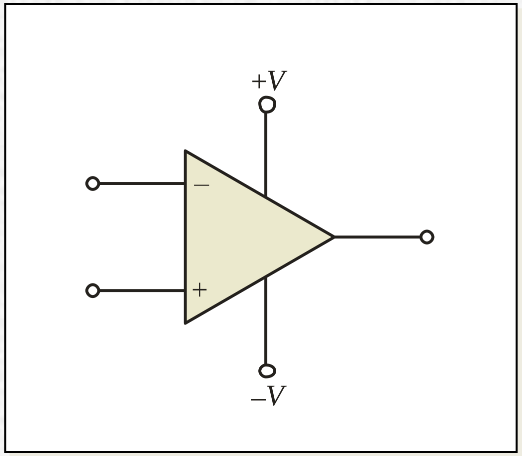
- Operational Amplifiers are represented both schematically and realistically below:
  - Active component!



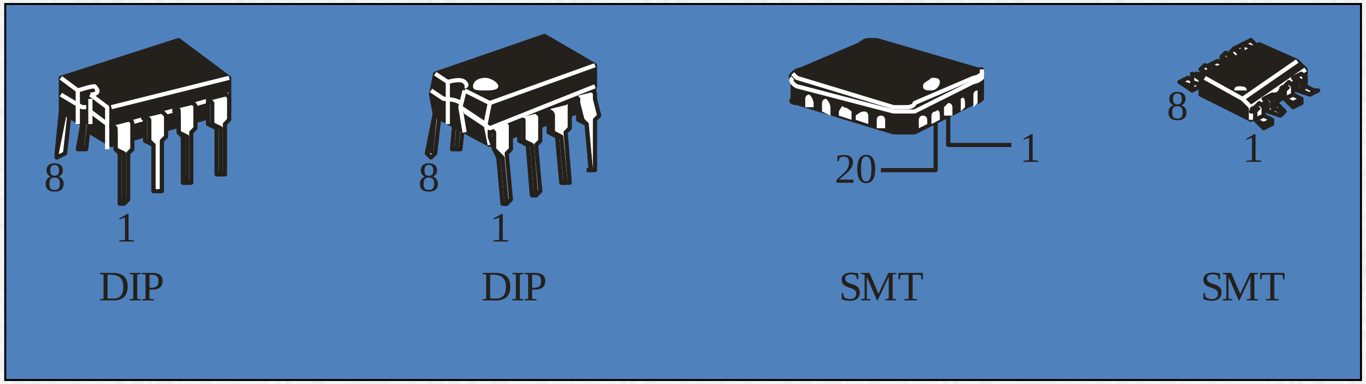

741
8-pin DIL (Dual In Line)
offset null 1
inverting input 2
non-inverting input 3
− V 4
8 not connected
7 + V
6 output
5 offset null
(viewed from above)

Operational Amplifers

Operational amplifiers (op-amps) are very high gain dc coupled amplifiers with differential inputs. One of the inputs is called the inverting input (–); the other is called the noninverting input. Usually there is a single output.

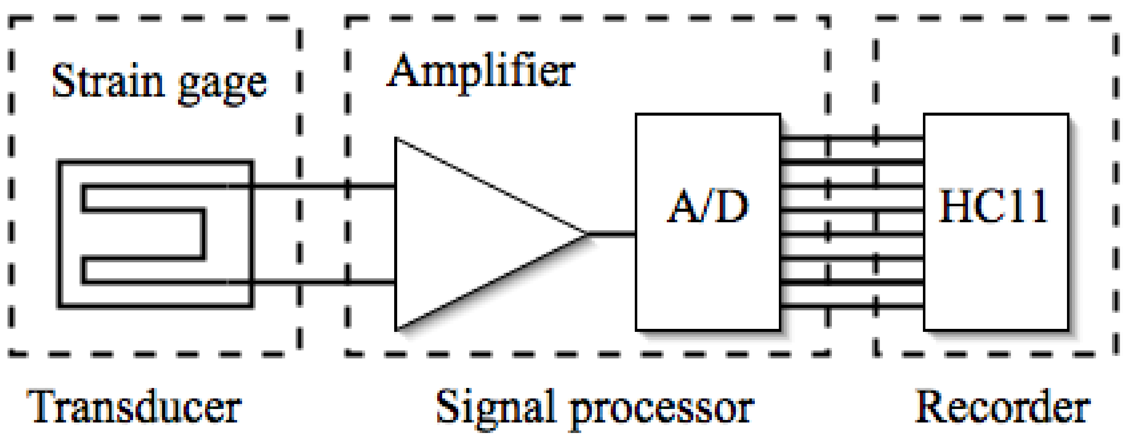


Most op-amps operate from plus and minus supply voltages, which may or may not be shown on the schematic symbol.

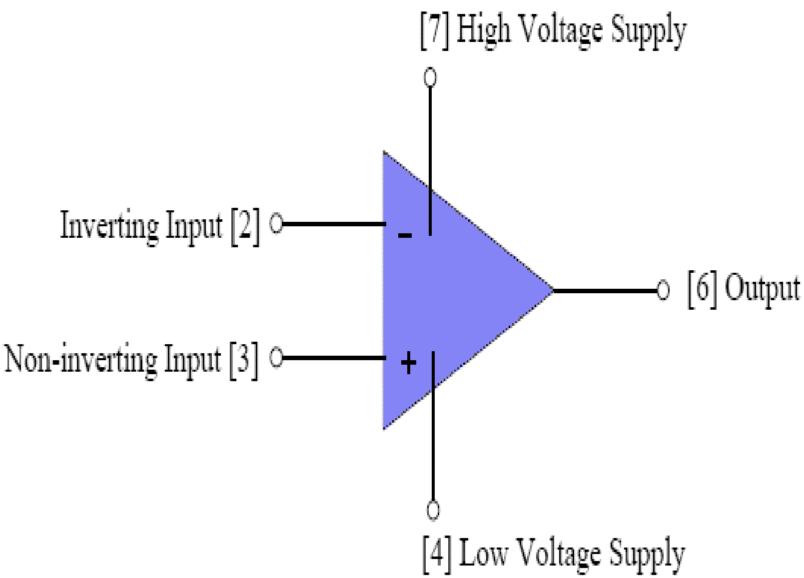


Why are they useful?

- Sensor signals are often too weak or too noisy
  - Op Amps ideally increase the signal amplitude without affecting its other properties



Operational Amplifier

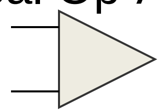


- Output gain high
  - A ~= 10^6
- Tiny difference in the input voltages result in a very large output voltage
  - Output limited by supply voltages
- Comparator
  - If $V_+ > V_-$, V_{out} = HVS
  - If $V_+ < V_-$, V_{out} = LVS
  - If $V_+ = V_-$, V_{out} = 0V

Ideal Op Amp

- Z_{in} is infinite
- Z_{out} is zero
- Amplification (Gain) $V_{out} / V_{in} = \infty$
- Unlimited bandwidth
- $V_{out} = 0$ when Voltage inputs = 0

Ideal Op Amp

	Ideal Op-Amp 	Typical Op-Amp 
Input Resistance	infinity	$10^6\ \Omega$ (bipolar) $10^9\ \Omega$ - $10^{12}\ \Omega$ (FET)
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

How are Op-Amps used?

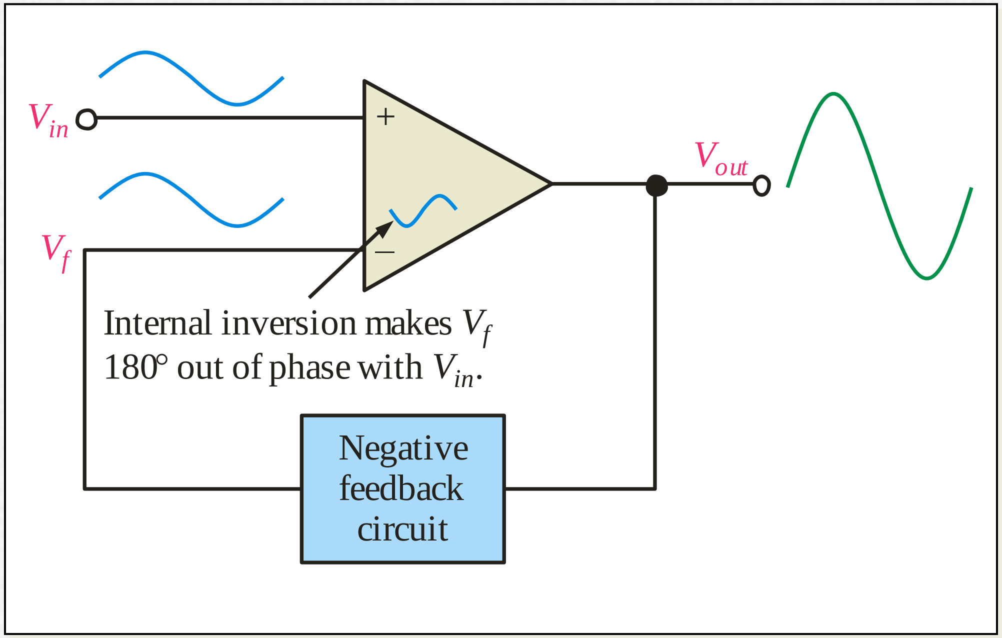
- Comparator (seen earlier)
- Voltage follower (seen earlier)
- Signal Modulation
- Mathematical Operations
- Filters
- Voltage-Current signal conversion

Summary

Negative Feedback

Negative feedback is the process of returning a portion of the output signal to the input with a phase angle that opposes the input signal.

The advantage of negative feedback is that precise values of amplifier gain can be set. In addition, bandwidth and input and output impedances can be controlled.

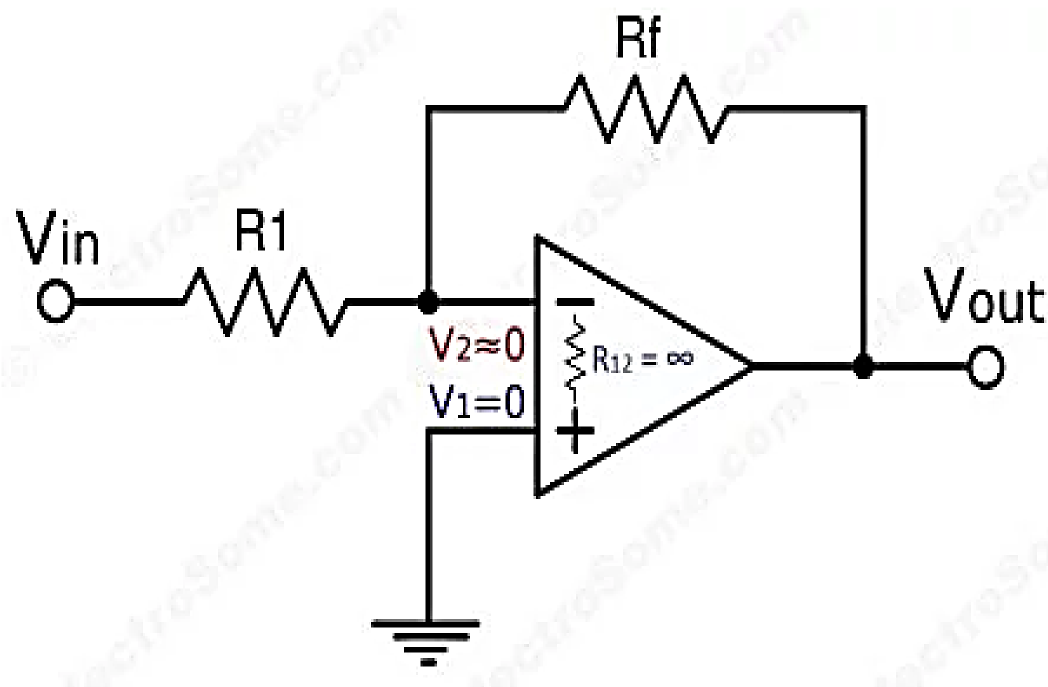


What is Virtual Ground ?

As the name indicates it is virtual, not real ground. For some purposes we can consider it as equivalent to ground. In op-amps **the term virtual ground means that the voltage at that particular node is almost equal to ground voltage** (0V). It is **not** physically connected to ground. This concept is very useful in analysis of op-amp circuits and it will make a lot of calculations very simple.

Virtual Ground – Opamp

Lets see how the virtual ground concept is employed in inverting amplier.



Virtual Ground – Inverting Amplifier using Opamp

Using Infinite Voltage Gain

We already know that an ideal op-amp will provide infinite voltage gain. For real op-amps also the gain will be very high such that we can consider it as infinite for calculation purposes.

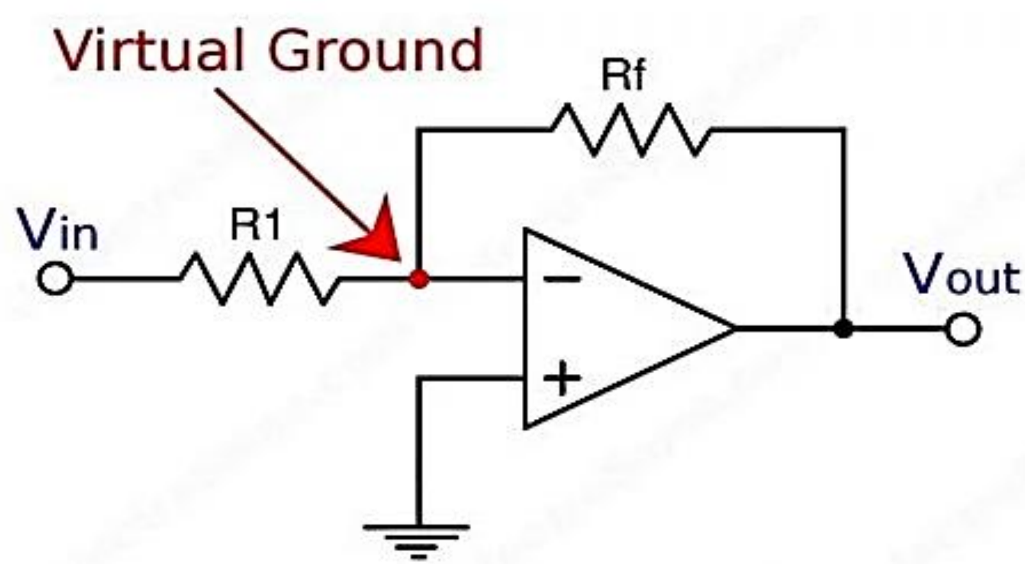
- **Gain = Vo/Vin**

As gain is infinite, **Vin = 0**

- Vin = V2 – V1

In the above circuit V1 is connected to ground, so V1 = 0. Thus V2 also will be at ground potential.

- **V2 = 0**



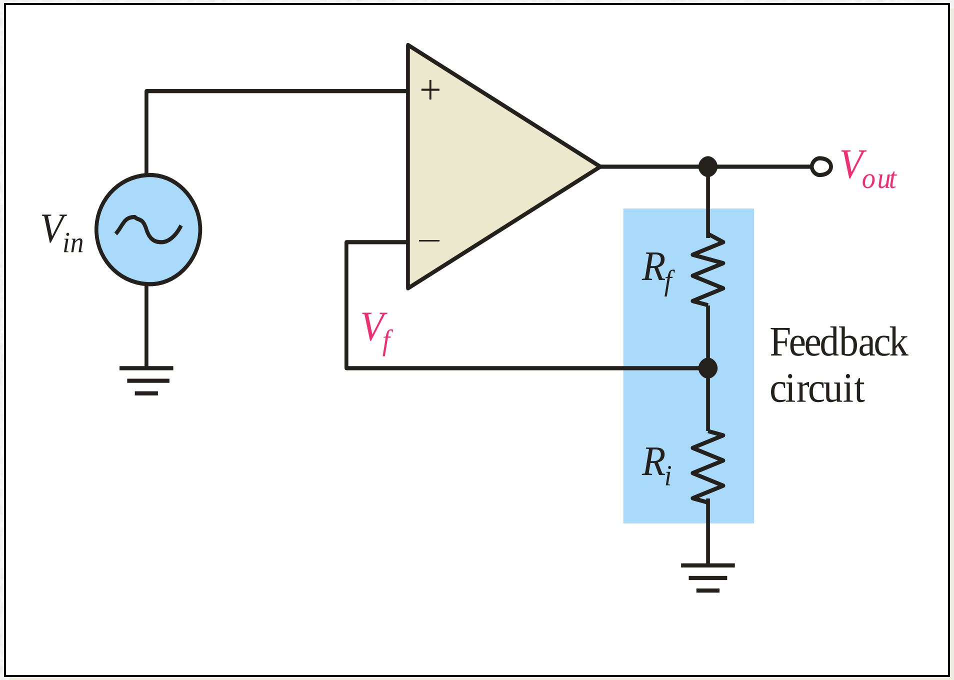
Summary

Noninverting Amplifier

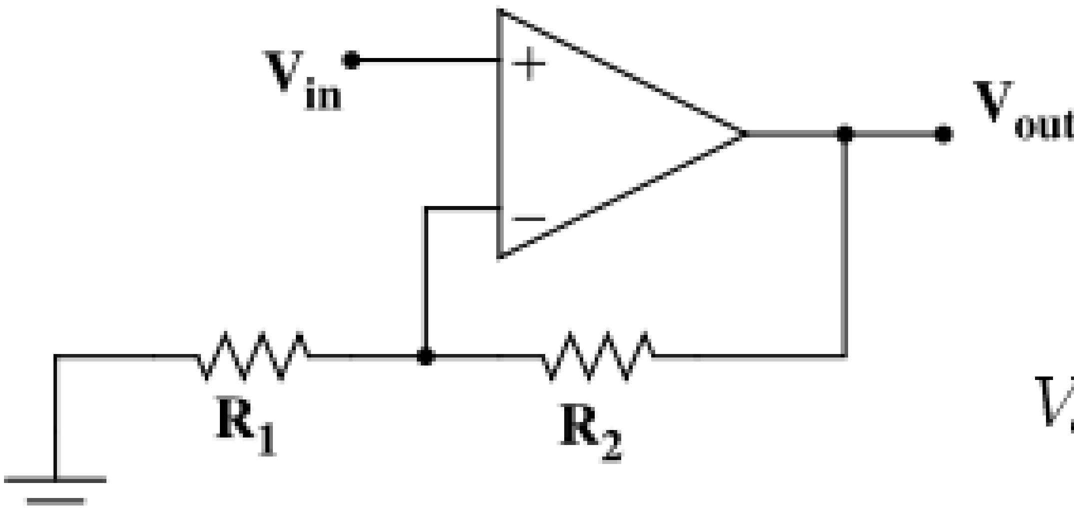
A **noninverting amplifier** is a configuration in which the signal is on the noninverting input and a portion of the output is returned to the inverting input.

Feedback forces V_f to be equal to V_{in}, hence V_{in} is across R_i. With basic algebra, you can show that the closed-loop gain of the noninverting amplifier is

$$A_{cl(\mathrm{NI})} = 1 + \frac{R_f}{R_i}$$



Non-inverting Op-Amp



$$V_{\mathrm{out}} = V_{\mathrm{in}} \left(1 + \frac{R_2}{R_1} \right)$$

Uses: Amplify…straight up

Summary

Noninverting Amplifier

Example:

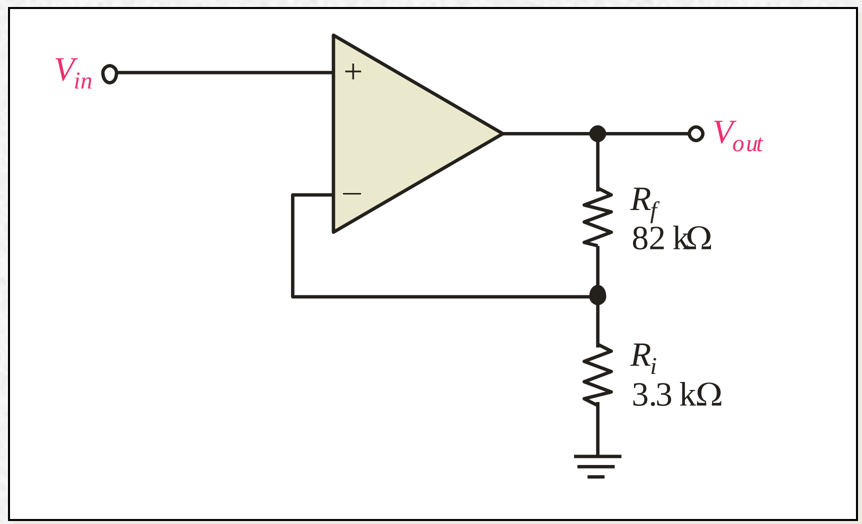
Determine the gain of the noninverting amplifier shown.

Solution:

$$A_{cl(\mathrm{NI})} = 1 + \frac{R_f}{R_i}$$

$$= 1 + \frac{82\ \mathrm{k\Omega}}{3.3\ \mathrm{k\Omega}}$$

= 35.8

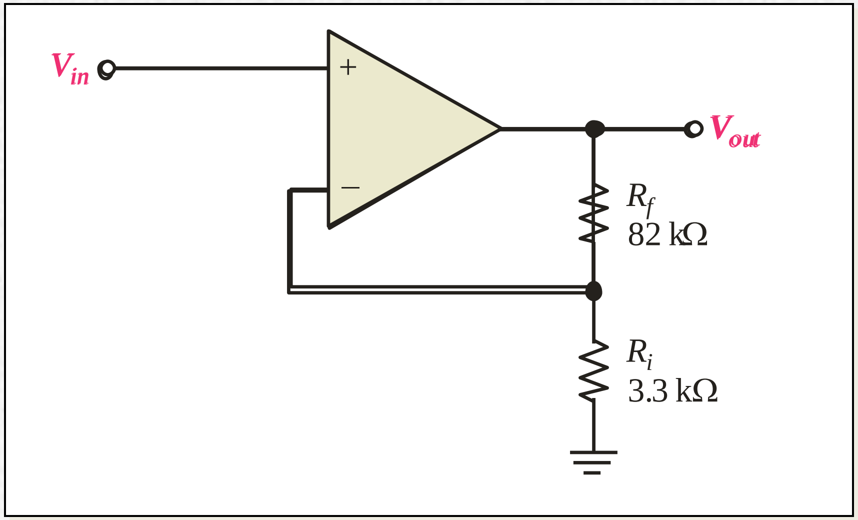


Summary

Noninverting Amplifier

A special case of the inverting amplifier is when R_f =0 and R_i = ∞. This forms a voltage follower or unity gain buffer with a gain of 1.

The input impedance of the voltage follower is very high, producing an excellent circuit for isolating one circuit from another, which avoids "loading" effects.



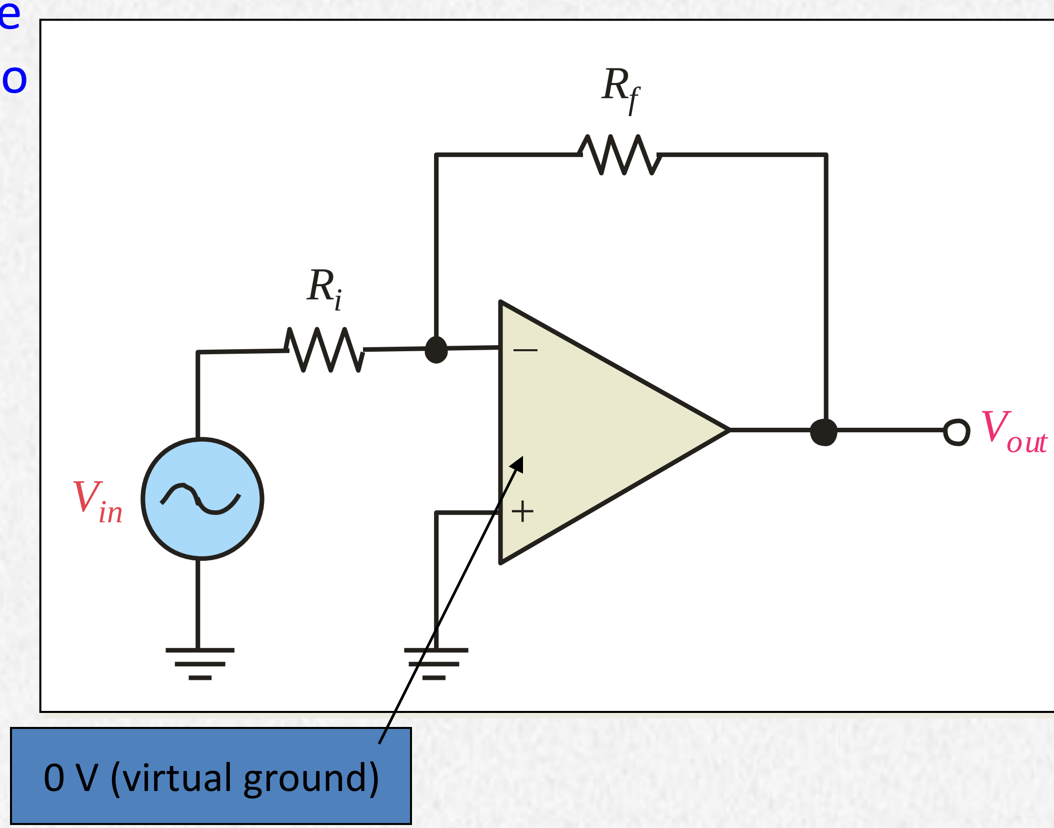
Summary

Inverting Amplifier

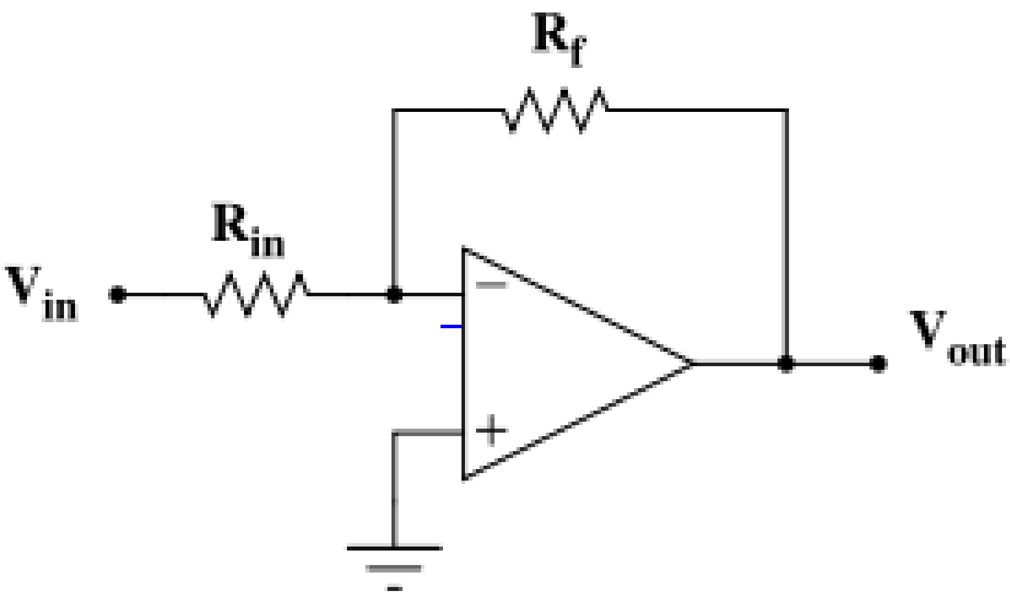
An **inverting amplifier** is a configuration in which the noninverting input is grounded and the signal is applied through a resistor to the inverting input.

Feedback forces the inputs to be nearly identical; hence the inverting input is very close to 0 V. The closed-loop gain of the inverting amplifier is

$$A_{cl(\mathrm{I})} = -\frac{R_f}{R_i}$$



Inverting Op-Amp



$$V_{\mathrm{out}} = -V_{\mathrm{in}}(R_{\mathrm{f}}/R_{\mathrm{in}})$$

Uses: Analog inverter

Summary

Inverting Amplifier

Example:

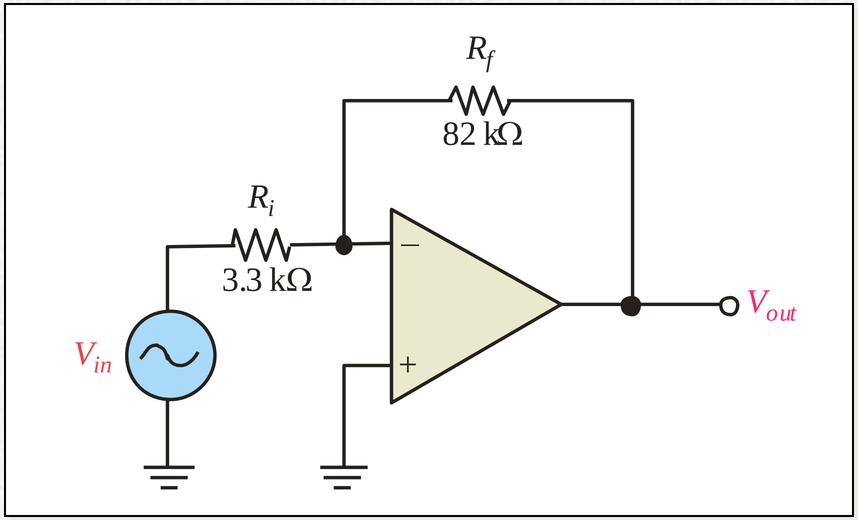
Determine the gain of the inverting amplifier shown.

Solution:

$$A_{cl(\mathrm{I})} = -\frac{R_f}{R_i}$$

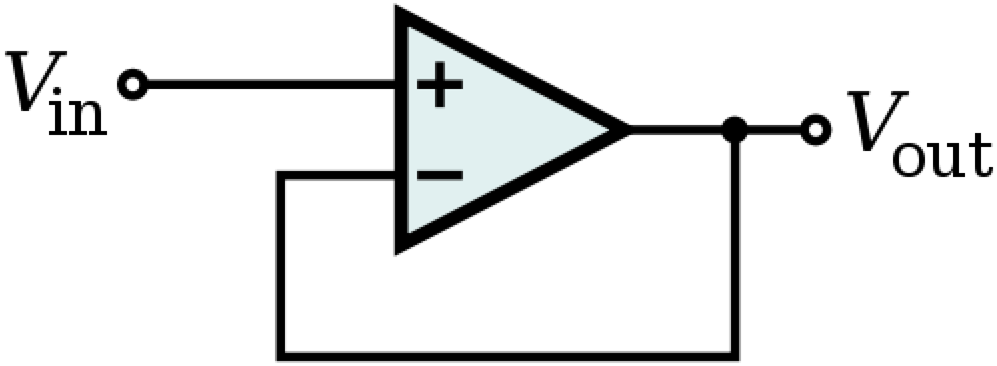
$$= -\frac{82\ \mathrm{k\Omega}}{3.3\ \mathrm{k\Omega}}$$

$$= -24.8$$



The minus sign indicates inversion.

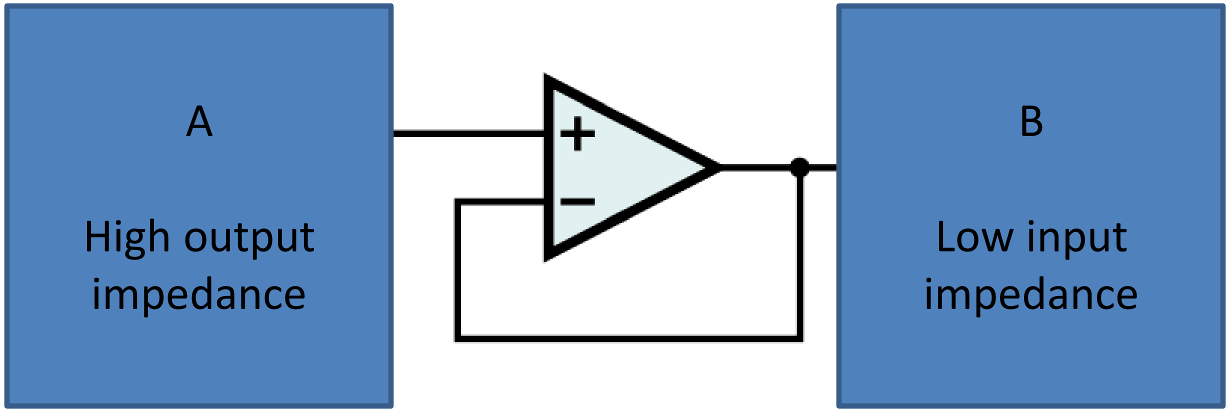
Op-Amp Buffer



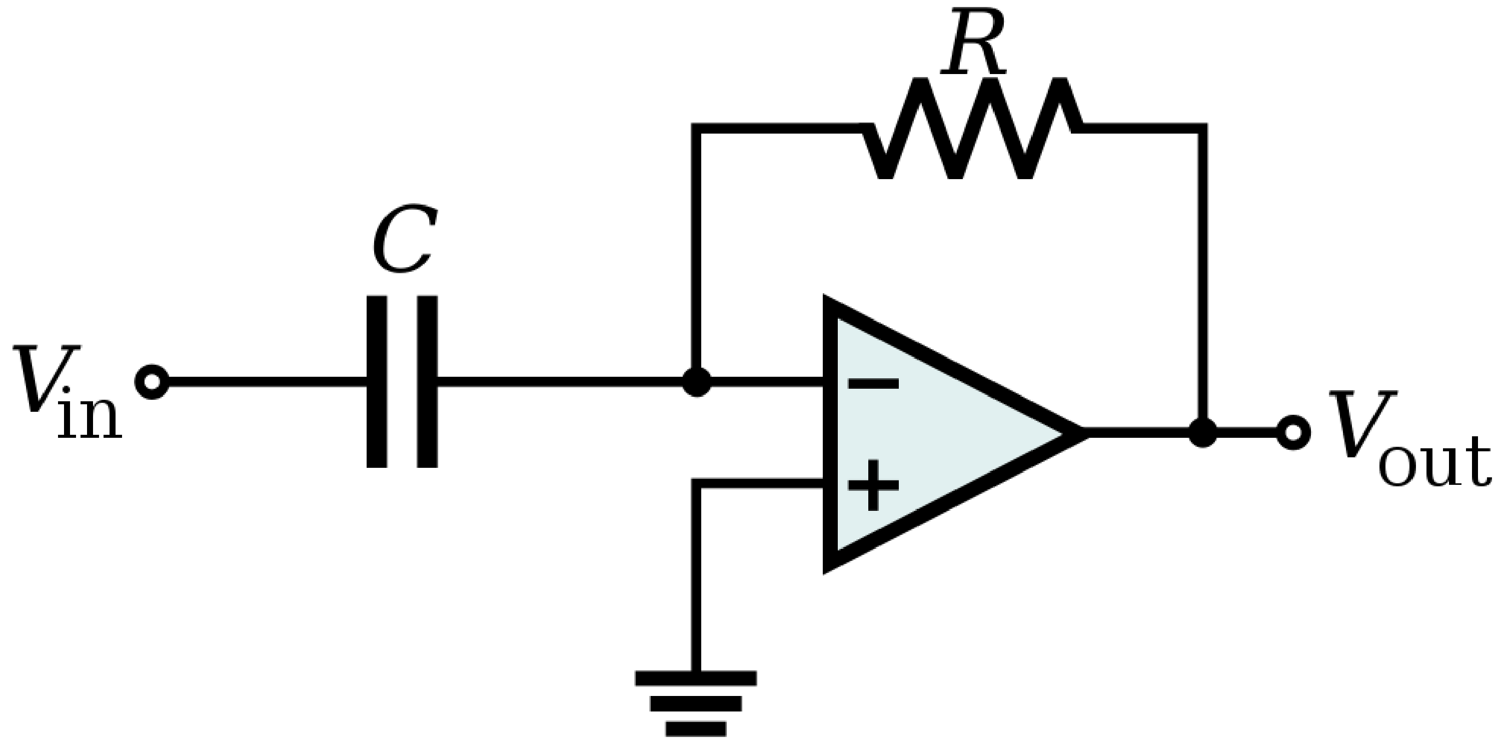
Vout = Vin
Isolates loading effects

The voltage follower or unity gain buffer circuit is commonly used to isolate different circuits, i.e. to separate one stage of circuit from another and also used in impedance matching applications.

In practice, the output voltage of a voltage follower will not be exactly equal to the input voltage applied and there will be a slight difference. This difference is due to the high internal voltage gain of the op-amp.

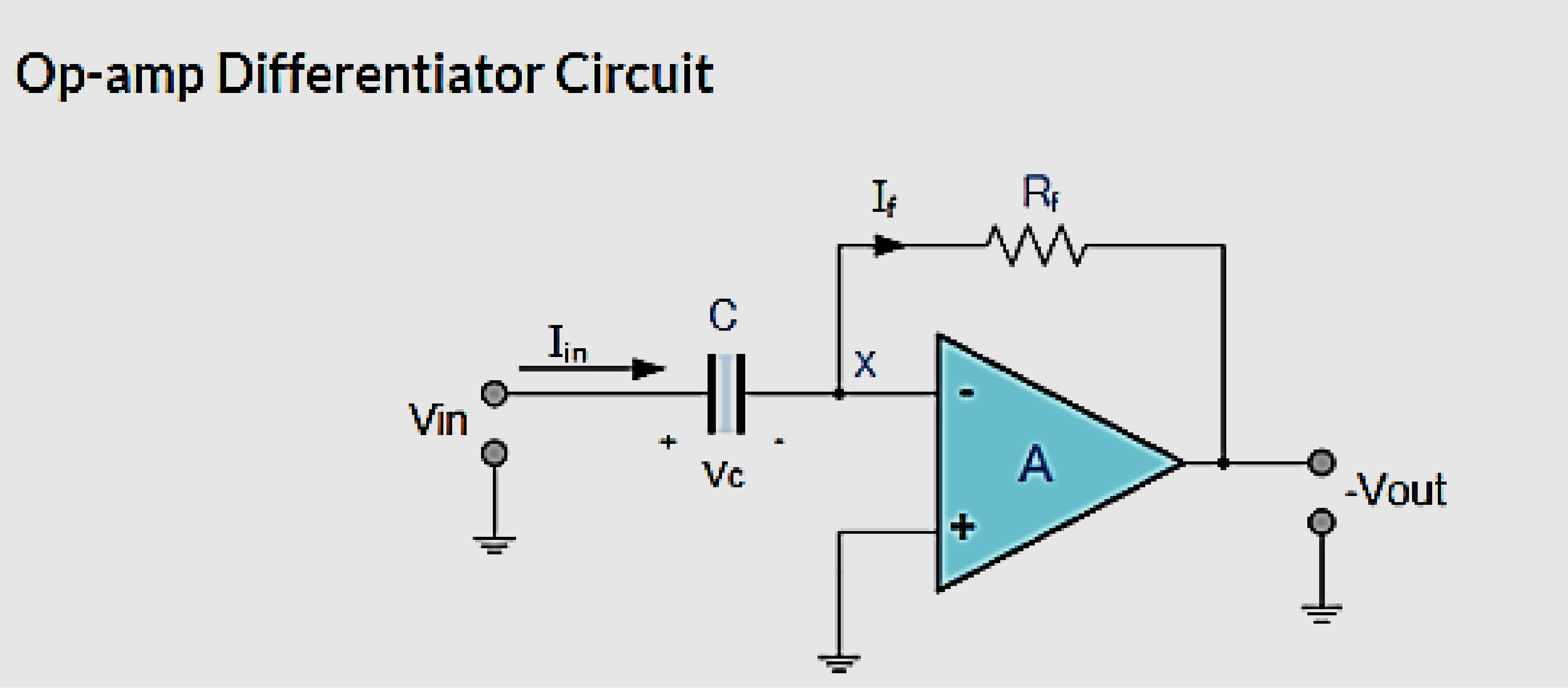


Op-Amp Differentiator



$$V_{out} = -RC \frac{\mathrm{d}V_{in}}{\mathrm{d}t}$$

Differentiator



$$I_{IN} = I_F \text{ and } I_F = -\frac{V_{OUT}}{R_F}$$

The charge on the capacitor equals Capacitance times Voltage across the capacitor

$$Q = C \times V_{IN}$$

Thus the rate of change of this charge is:

$$\frac{dQ}{dt} = C\frac{dV_{IN}}{dt}$$

but dQ/dt is the capacitor current, *i*

$$I_{IN} = C\frac{dV_{IN}}{dt} = I_F$$

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

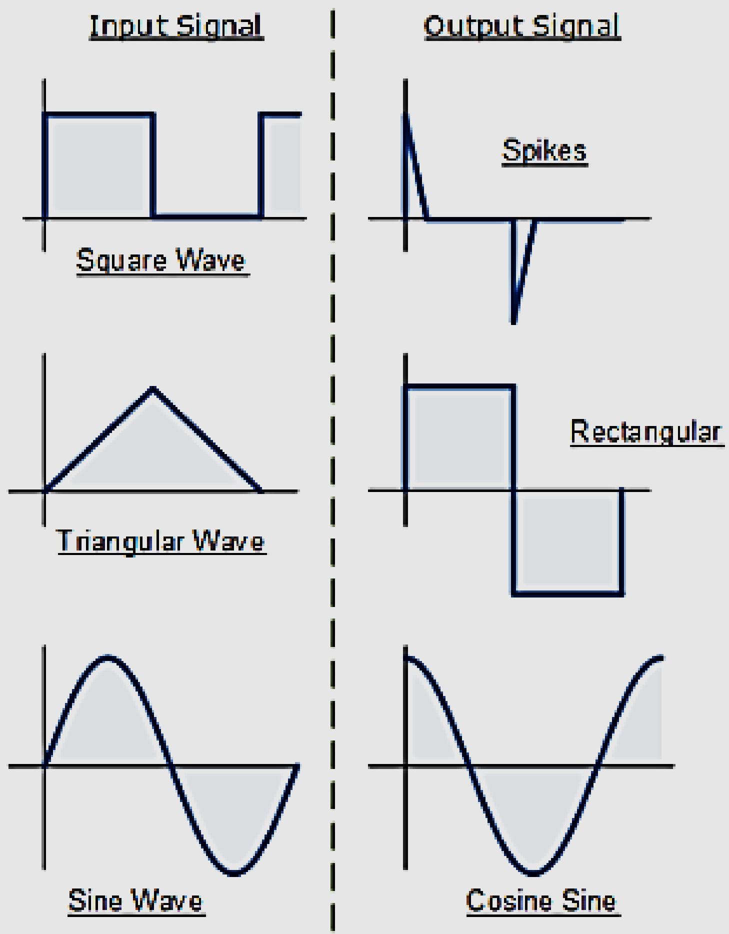
from which we have an ideal voltage output for the op-amp differentiator is given as:

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

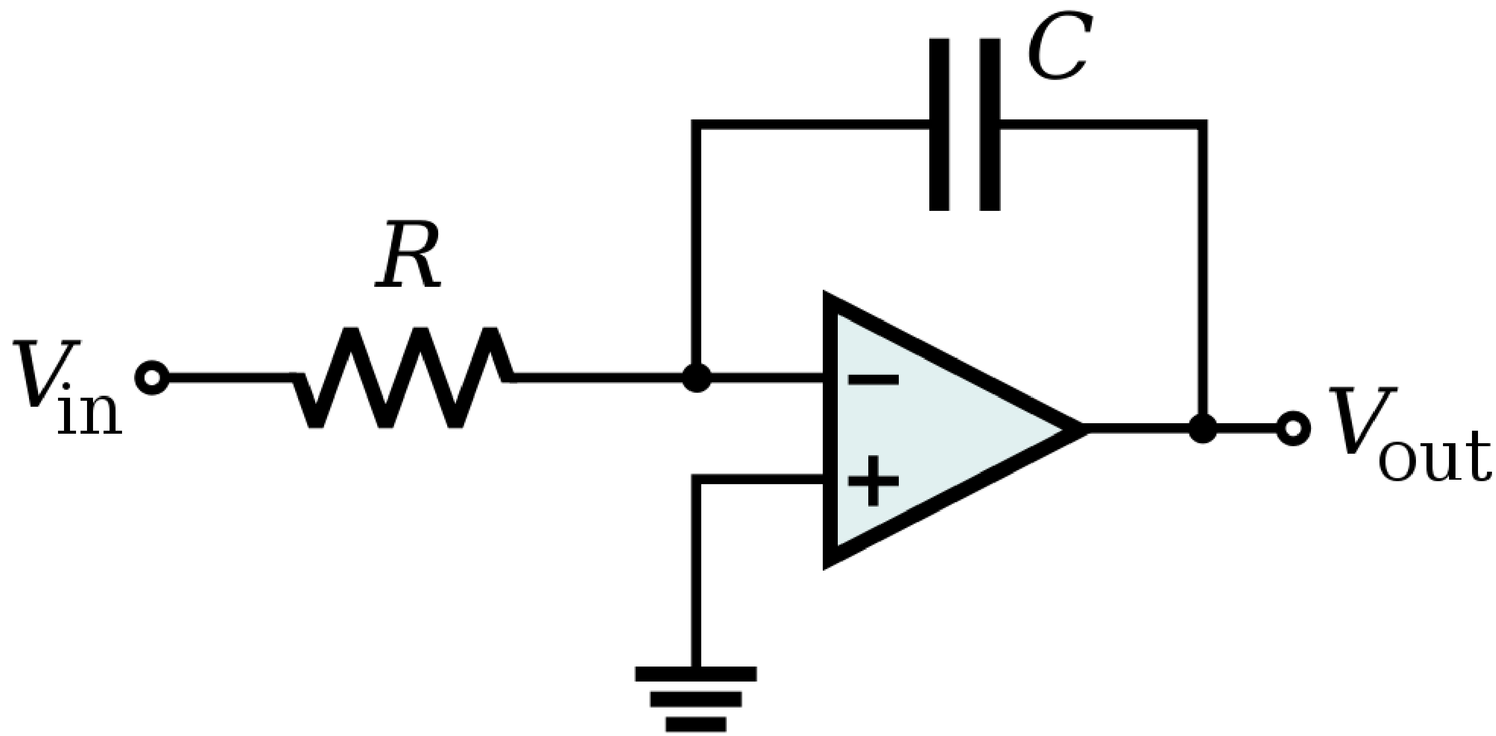
Therefore, the output voltage Vout is a constant –Rf*C times the derivative of the input voltage Vin with respect to time. The minus sign (–) indicates a 180^{o} phase shift because the input signal is connected to the inverting input terminal of the operational amplifier.

Op-amp Differentiator Waveforms

If we apply a constantly changing signal such as a Square-wave, Triangular or Sine-wave type signal to the input of a differentiator amplifier circuit the resultant output signal will be changed and whose final shape is dependant upon the RC time constant of the Resistor/Capacitor combination.

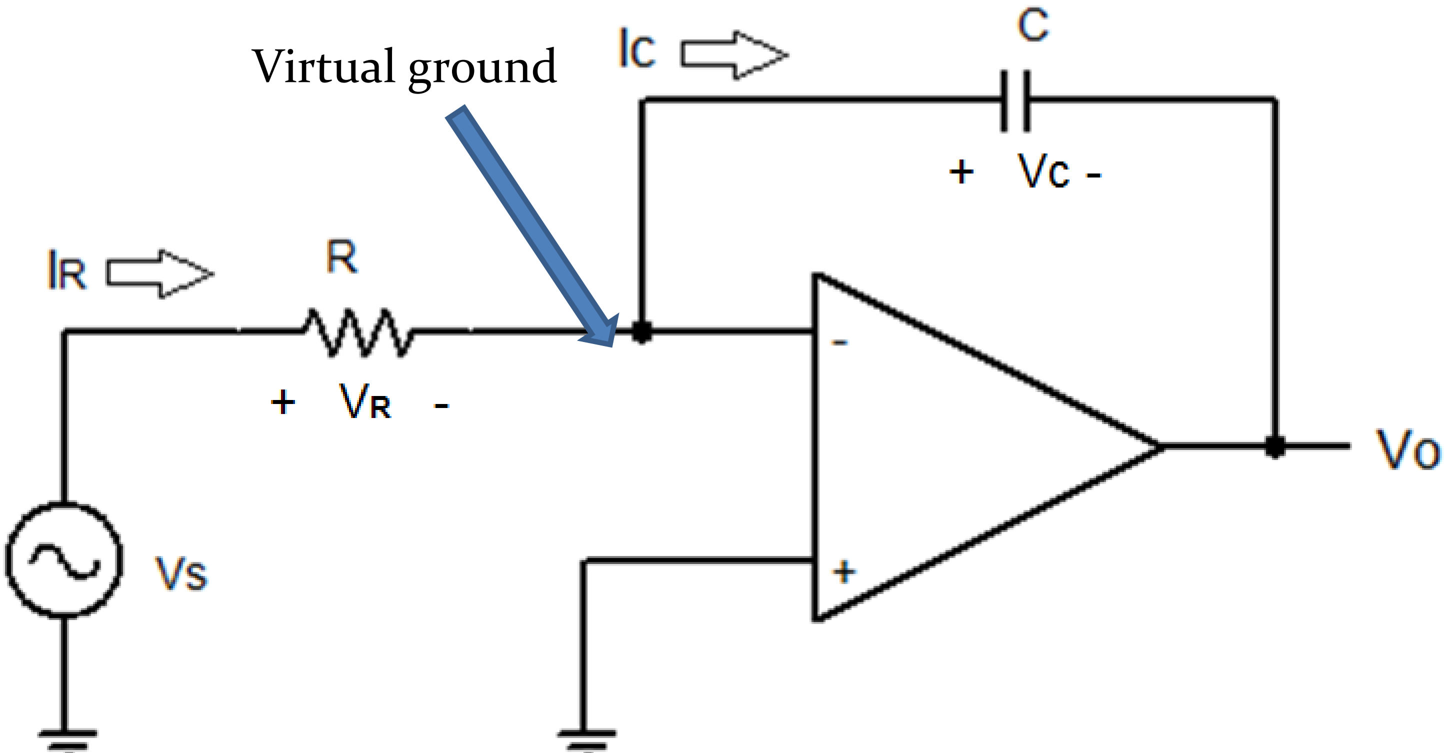


Op-Amp Integrator

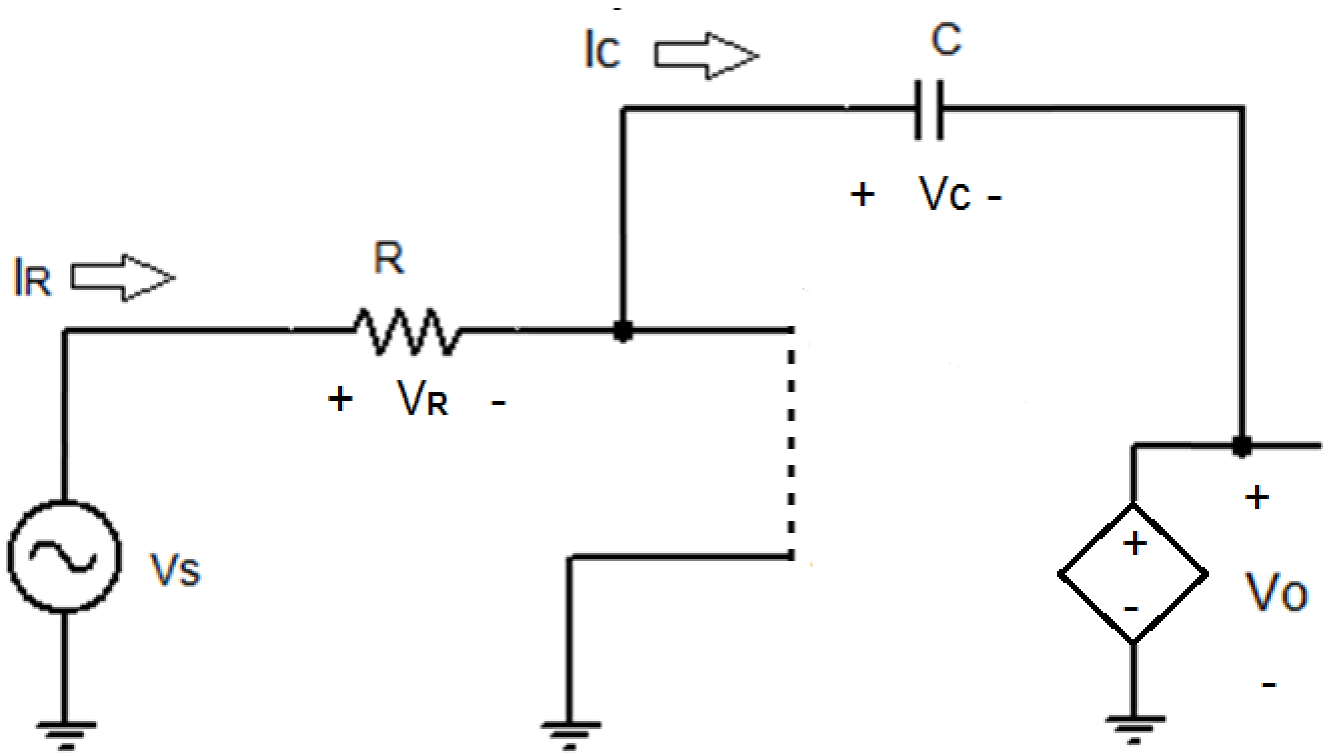


$$V_{\text{out}} = -\int_0^t \frac{V_{\text{in}}}{RC}\,\mathrm{d}t + V_{\text{initial}}$$

Integrator



Op Amp Model



Integrator

$$i_R = \frac{v_S(t) - v_1}{R} = \frac{v_S(t)}{R}$$

$$i_C = C\frac{dv_C}{dt}$$

$$v_C(t) = v_1 - v_o(t) = -v_o(t)$$

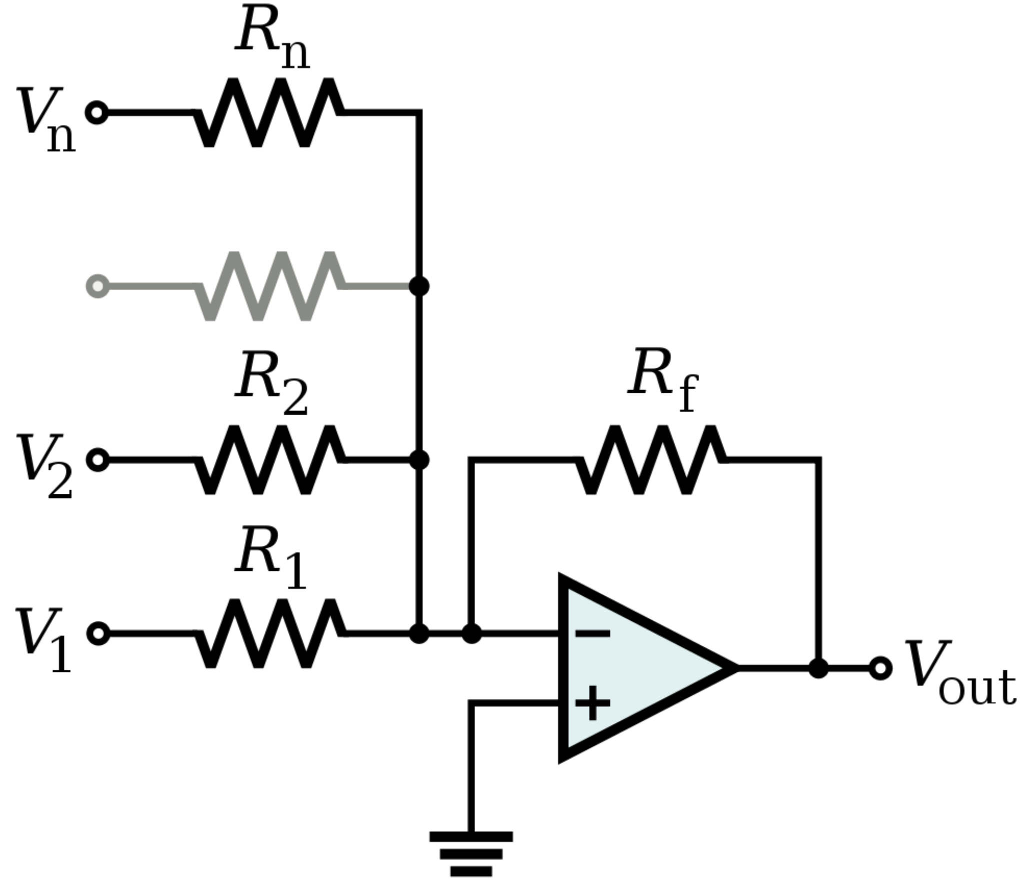
$$i_R - i_C = 0mA$$

$$\frac{v_S(t)}{R} - C\frac{d\left[-v_o(t)\right]}{dt} = 0$$

$$\frac{dv_o(t)}{dt} + \frac{v_S(t)}{RC} = 0$$

$$v_o(t_2) = \frac{-1}{RC}\int_{t_1}^{t_2} v_S(t)dt + v_o(t_1)$$

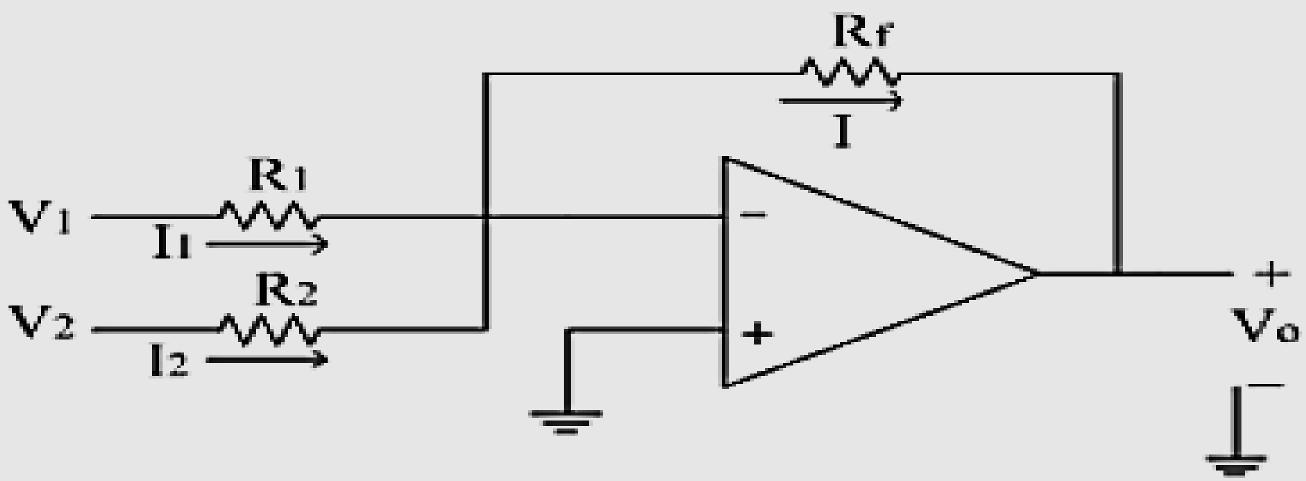
Op-Amp Summing Amplifier



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

Inverting adder:

The input signals to be added are applied to the inverting input terminal of op-amp. The following figure shows the inverting adder using op-amp with two inputs V1 and V2.



Let us assume currents I1 and I2 are flowing through resistances R1 and R2 respectively. Since input current to the op-amp is zero, the two currents are added to get current I, which flows through the feedback resistance Rf.

Thus by KCL at inverting terminal, we get

$$I = I_1 + I_2$$

Substituting for the currents,

$$\frac{0-V_o}{R_f}=\frac{V_1-0}{R_1}+\frac{V_2-0}{R_2}$$

$$\therefore \frac{-V_o}{R_f}=\frac{V_1}{R_1}+\frac{V_2}{R_2}$$

$$\therefore V_o=-\left[\frac{R_f V_1}{R_1}+\frac{R_f V_2}{R_2}\right]$$

Thus the above equation gives the weighted addition of the two input signals (in the form mX + n Y, where m and n are the weights of inputs X and Y respectively)

If R1=R2=R

$$\therefore \quad V_o=-\frac{R_f}{R_1}\left[V_1+V_2\right]$$

Thus the addition of the two input signals obtained with gain [-Rf/R]

If Rf=R,

$$\therefore \quad V_o = -[V_1 + V_2]$$

Thus the addition of two inputs obtained. The negative sign indicates that input and output are having 180° phase shift.

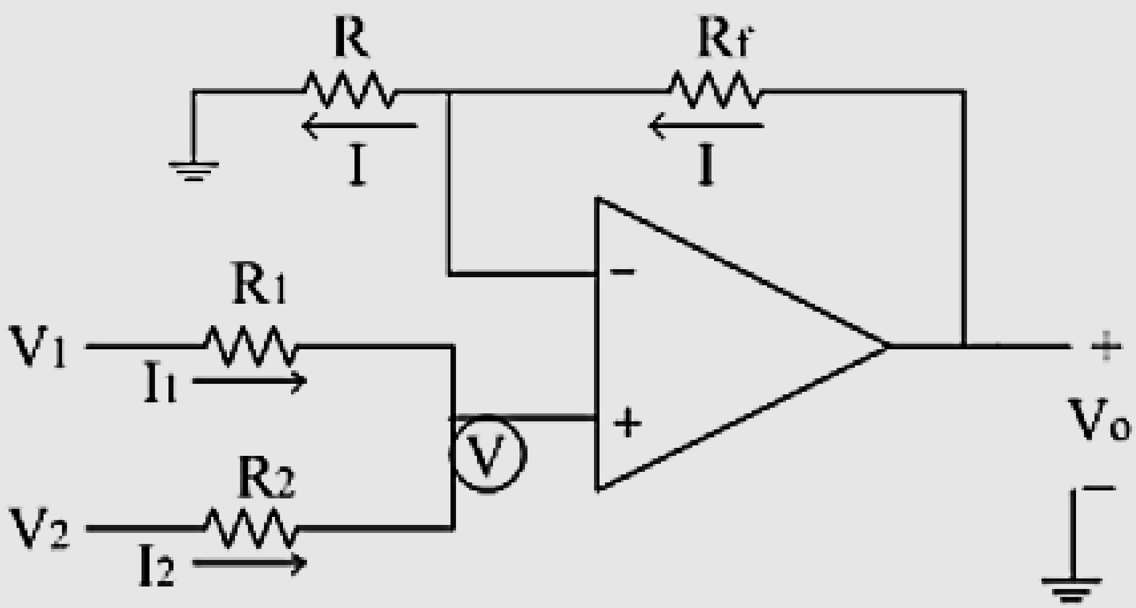
The above circuit can also be used to get the average of the two inputs, with the following substitution. Thus the circuit can be used as an averager.

If R=2Rf

$$\therefore \quad V_o = -\left(\frac{V_1 + V_2}{2}\right)$$

Non-inverting adder:

The input signals to be added are applied to the non-inverting input terminal of op-amp. The following figure shows the non- inverting adder using op-amp with two inputs V1 and V2.



Let us assume currents I1 and I2 are flowing through resistances R1 and R2 respectively. Since input current to the op-amp is zero, the addition of the two currents is zero at non-inverting terminal.

Let the non-inverting terminal is at potential 'V'. Due to virtual ground concept, the inverting terminal appears to be at the same potential 'V'.

Thus by applying KCL at non-inverting terminal we get,

$$I_1+I_2=0$$

Substituting for the currents, we get

$$\frac{V_1-V}{R_1}+\frac{V_2-V}{R_2}=0$$

$$\therefore \quad \frac{V_1}{R_1}+\frac{V_2}{R_2}=V\left[\frac{1}{R_1}+\frac{1}{R_2}\right]$$

$$\therefore \quad V\left[\frac{R_1+R_2}{R_1R_2}\right]=\left[\frac{V_2R_1+V_1R_2}{R_1R_2}\right]$$

$$\therefore \quad V=\left[\frac{V_2R_1+V_1R_2}{R_1+R_2}\right]$$

The current 'I' from the feedback path is given as,

$$I= \left[\frac{V_o-V}{R_f}\right]=\left[\frac{V-0}{R}\right]$$

Solving the above equation for Vo, we get

$$\frac{V_o}{R_f} - \frac{V}{R_f} = \frac{V}{R}$$

$$\therefore \quad \frac{V_o}{R_f} = V\left[\frac{R_f+R}{RR_f}\right]$$

$$\therefore \quad V_o = V\left[\frac{R_f+R}{R}\right]$$

Substituting voltage 'V' from equation (1) in above Vo equation

$$V_o = \left[\frac{V_1R_2+V_2R_1}{R_1+R_2}\right]\left[\frac{R_f+R}{R}\right]$$

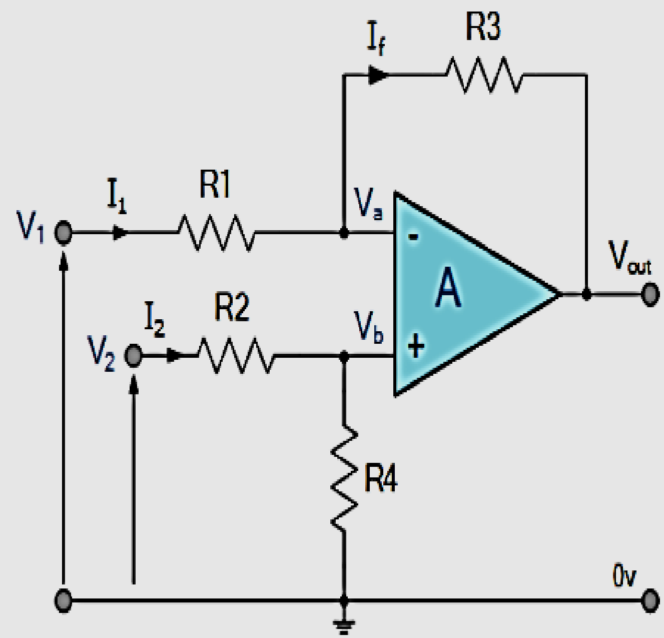
$$\therefore \quad V_o = V_1\left[\frac{R_2(R_f+R)}{(R_1+R_2)R_2}\right] + V_2\left[\frac{R_1(R_f+R)}{(R_1+R_2)R_2}\right]$$

If R1=R2=R=Rf

∴Vo=V1+V2

The Differential Amplifier

The differential amplifier amplifies the voltage difference present on its inverting and non-inverting inputs



By connecting each input in turn to 0v ground we can use superposition to solve for the output voltage Vout. Then the transfer function for a **Differential Amplifier** circuit is given as:

$$I_1 = \frac{V_1 - V_a}{R_1}, \quad I_2 = \frac{V_2 - V_b}{R_2}, \quad I_f = \frac{V_a - (V_{out})}{R_3}$$

Summing point $V_a = V_b$

and $V_b = V_2 \left(\frac{R_4}{R_2 + R_4} \right)$

If $V_2 = 0$, then: $V_{out(a)} = -V_1 \left(\frac{R_3}{R_1} \right)$

If $V_1 = 0$, then: $V_{out(b)} = V_2 \left(\frac{R_4}{R_2 + R_4} \right) \left(\frac{R_1 + R_3}{R_1} \right)$

$$V_{out} = -V_{out(a)} + V_{out(b)}$$

$$\therefore\ V_{out} = -V_1\left(\frac{R_3}{R_1}\right) + V_2\left(\frac{R_4}{R_2+R_4}\right)\left(\frac{R_1+R_3}{R_1}\right)$$

When resistors, R1 = R2 and R3 = R4 the above transfer function for the differential amplifier can be simplified to the following expression:

$$\boxed{V_{OUT} = \frac{R_3}{R_1}\left(V_2 - V_1\right)}$$

If all the resistors are all of the same ohmic value, that is: R1 = R2 = R3 = R4 then the circuit will become a **Unity Gain Differential Amplifier** and the voltage gain of the amplifier will be exactly one or unity. Then the output expression would simply be Vout = $V_2 - V_1$.

Also note that if input V1 is higher than input V2 the output voltage sum will be negative, and if V2 is higher than V1, the output voltage sum will be positive.

Common Mode Rejection Ratio (CMRR)

The ability to reject common mode signal is called Common Mode Rejection Ratio (CMRR). It can also be defined as the ratio of differential gain to common mode gain.

CMRR = *|differential gain/common mode gain|*

= *|Ad/Ac|*

Unit of CMRR is dB

CMRR = *20log|Ad/Ac|*