Course: Basic Electronics (EC21101)

Course Instructor: Prof. Kapil Debnath

Lecture 8: OPAMP

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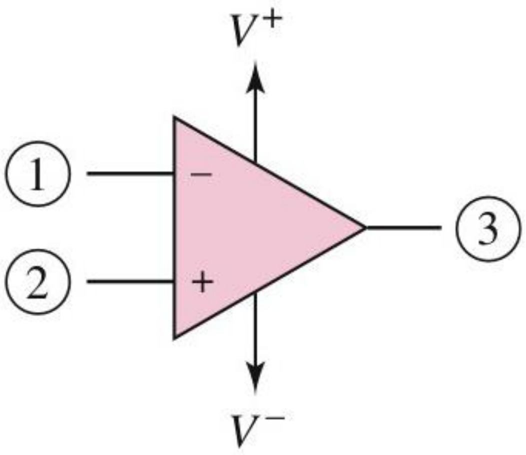
Op-amp: introduction

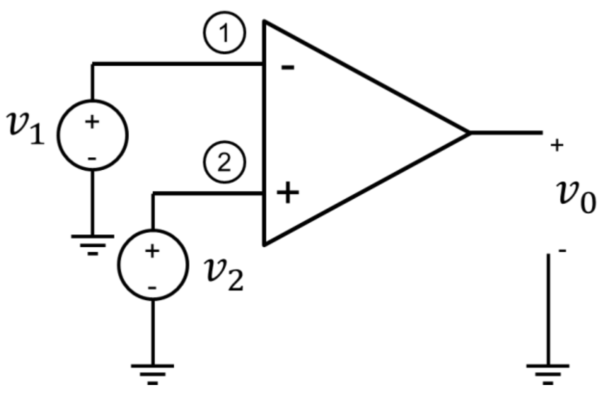
- An Op-Amp or simply opamp (short for operational amplifier) is an integrated circuit (IC) consisting of multiple transistors (either BJT or MOSFET), resistances and capacitors.
- The Operational Amplifier (Op-Amp) is a versatile building block that can be used for realizing several analog electronic circuits.
- Opamp is a DC-coupled high-gain electronic voltage amplifier. i.e. the input and output signals can be directly coupled to the device, without the need for coupling capacitors.
- Opamp has two input ports and one output port.
- An opamp circuit amplifies the difference between two input voltages and produces a single output.
- The characteristics of an op-amp are nearly ideal, i.e. op-amp circuits can be expected to perform as per theoretical design in most cases.
- The user can generally carry out circuit design using opamp without a thorough knowledge of the intricate details of an op-amp. This makes the circuit design process simple.
- In this course we will treat omamp as a discrete component same as a BJT or a diode.

Op-amp: circuit and symbol

Op-amp symbol:



- 2 inputs (terminal 1 and terminal 2)
- 1 output
- 2 DC biasing (V^+ and V^-)
- Sometimes the DC biasing points are not shown in the symbol
- Terminal 1: inverting input terminal
- Terminal 2: Noninverting input terminal
- Terminal 3: output terminal

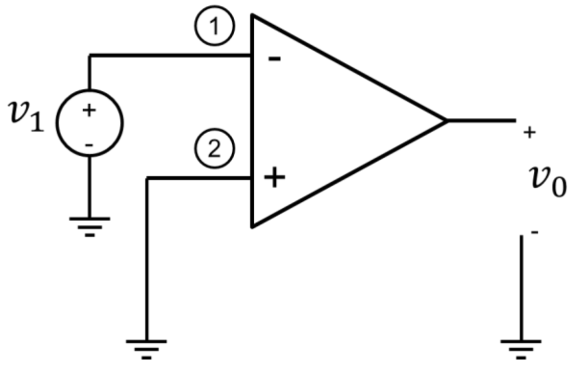


- An ideal op-amp only amplifies the difference of two input signals. (*we will discuss non-ideal op-amp later in this chapter*)
- For an ideal op-amp the input-output relationship is given as:

$$v_0 = A_{od}(v_2 - v_1)$$

Op-amp: circuit and symbol

Inverting terminal:

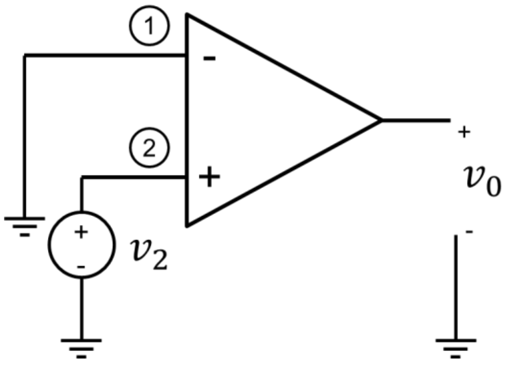


- Input terminal 1 is called inverting terminal, because when signal is applied only to terminal 1 and terminal 2 is grounded we get

$$v_0 = -A_{od}v_1$$

That is the output is an amplified inverted version of the input signal.

noninverting terminal:

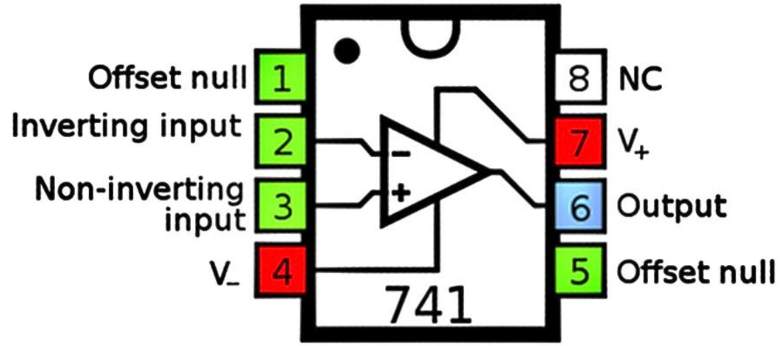


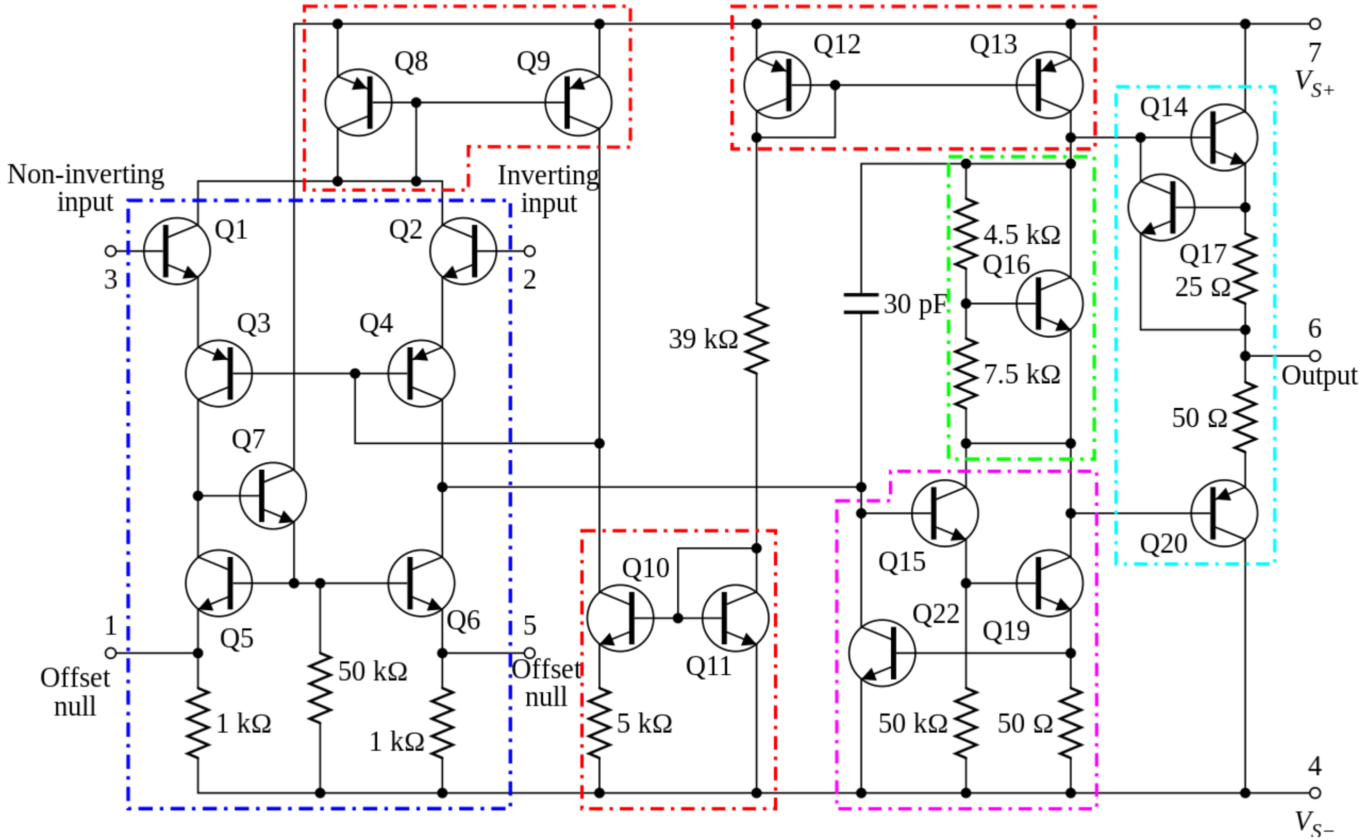
- Input terminal 2 is called noninverting terminal, because when signal is applied only to terminal 2 and terminal 1 is grounded we get

$$v_0 = A_{od}v_2$$

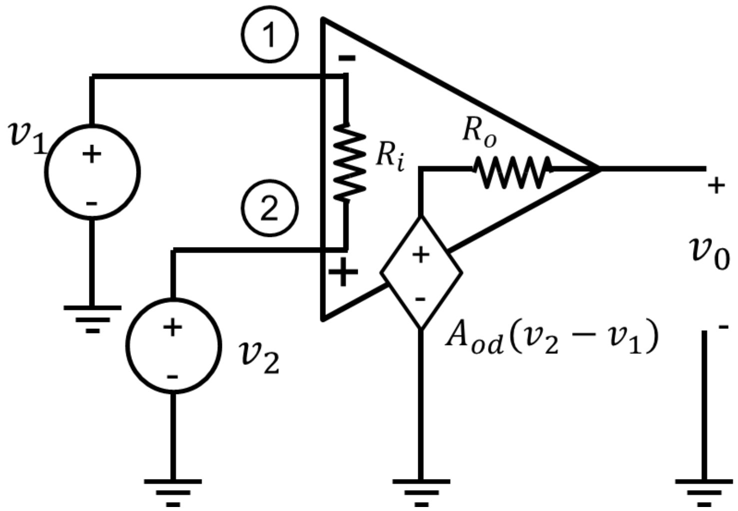
That is the output is simply an amplified version of the input signal.

Op-amp: circuit and symbol





Op-amp: Equivalent circuit



- R_i: input resistance
- R_o: output resistance
- A_{od}: open-loop voltage gain
- It is a voltage controlled voltage source

Ideal op-amp

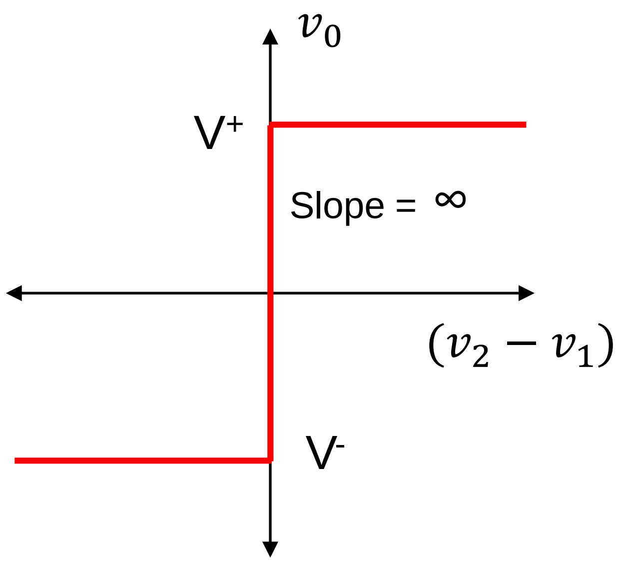
- $R_i \to \infty$
- $R_o \to 0$
- $A_{od} \to \infty$
- bandwidth$\to \infty$

Real op-amp

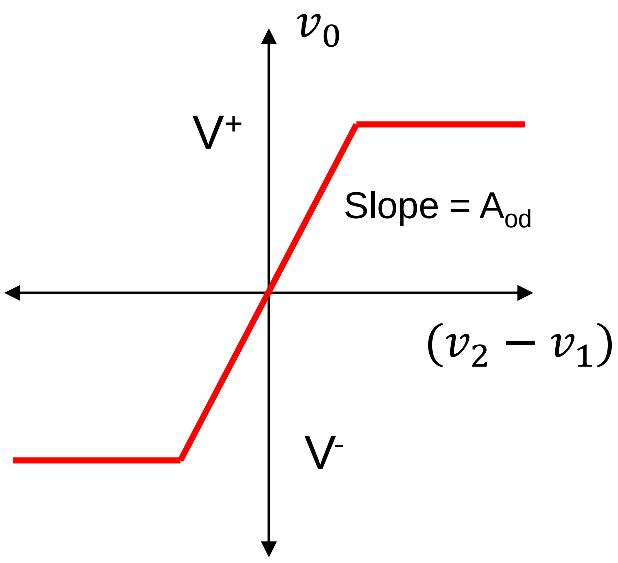
- R_i in MΩ (2MΩ)
- R_o in few Ω (75Ω)
- A_{od} finite (2×10^5)
- Finite bandwidth

Op-amp: input-output characteristics

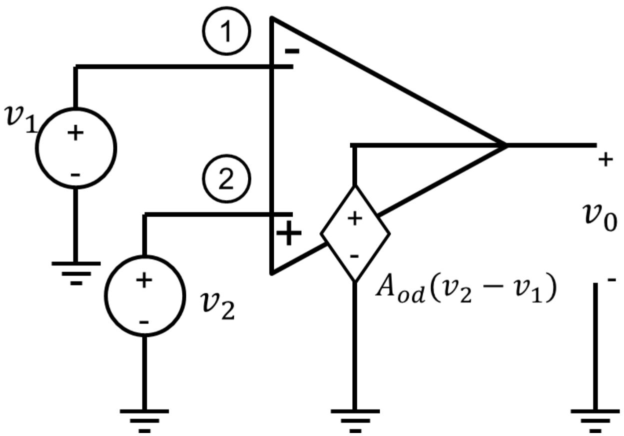
Ideal op-amp



Real op-amp



Ideal Op-amp

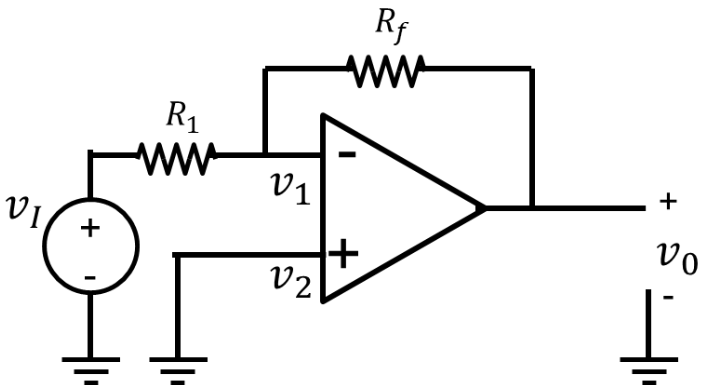


For an ideal op-amp

- No current flows between the two input terminals ($R_i \rightarrow \infty$)
- Output voltage is independent of load current ($R_o \rightarrow 0$)
- For $(v_2 - v_1) \neq 0$, the output voltage becomes ∞ or in other words saturates at either of the DC biasing voltages.

- Op-amps are never used in open loop configuration due to high voltage amplification.
- For most of the applications Op-amps are used in a negative feedback configuration.
- In a negative feedback system a fraction of the output signal, either a voltage or a current, is sent back to the input and subtracted from the actual input signal. Negative feedback improves the stability of the system.
- In some applications positive feedback is also used (such as oscillator), i.e. the output fraction is added to the original input signal. But we will not discuss this in this course.

Inverting amplifier (using ideal op-amp)

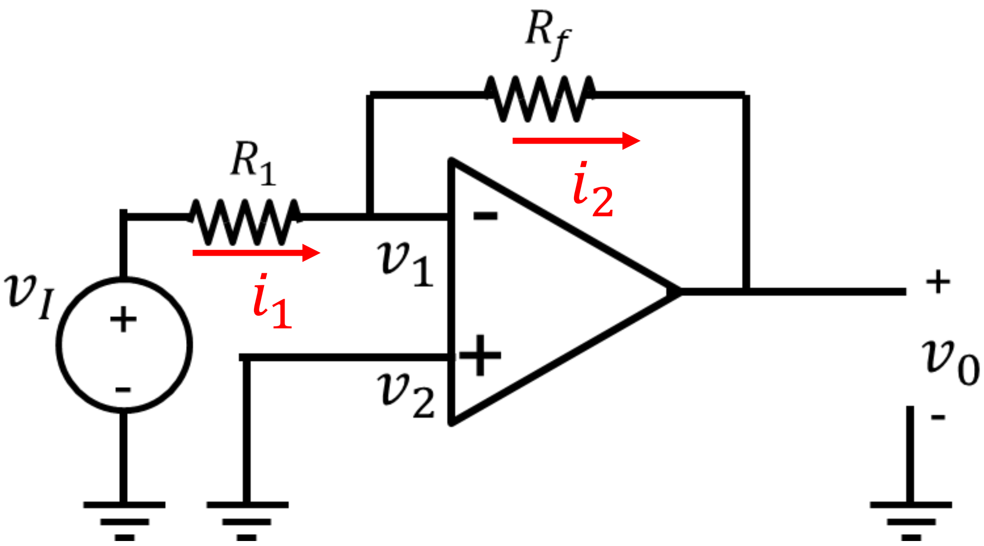


- The circuit shows a inverting amplifier configuration using op-amp.
- A fraction of the output voltage is fed back through the resistance R_f to the inverting terminal of the op-amp, thus acting as a negative feedback.
- The output voltage is given as:

$$v_0 = A_{od}(v_2 - v_1)$$

- Since v_0 needs to be finite and for ideal op-amp A_{od} is ∞, therefore $(v_2 - v_1)$ has to be equal to zero.
- In other words, $v_2 = v_1$, that is both the input terminals of the op-amp has the same voltage.
- However, we know that the resistance between the two input terminals is ∞ $(R_i \rightarrow \infty)$, so no current flows between the two terminals.
- This situation is called "*virtual short*".
- In case of an inverting amplifier, $v_2 = 0$, hence $v_1 = 0$. Hence, even though terminal 1 is not connected to the ground, it is at ground potential due to "*virtual short*" between terminal 1 and terminal 2.
- Terminal is called to be at "*virtual ground*".

Inverting amplifier (using ideal op-amp)



- Lets consider current through R_1 is i_1 and current through R_f is i_2.
- Since $v_1 = v_2 = 0$

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

And

$$i_2 = \frac{v_1 - v_o}{R_f} = -\frac{v_o}{R_f}$$

- Since no current flow into the op-amp through terminal 1,

$$i_1 = i_2$$

- i.e.

$$\frac{v_I}{R_1} = -\frac{v_o}{R_f}$$

Therefore voltage gain

$$A_v = \frac{v_o}{v_I} = -\frac{R_f}{R_1}$$

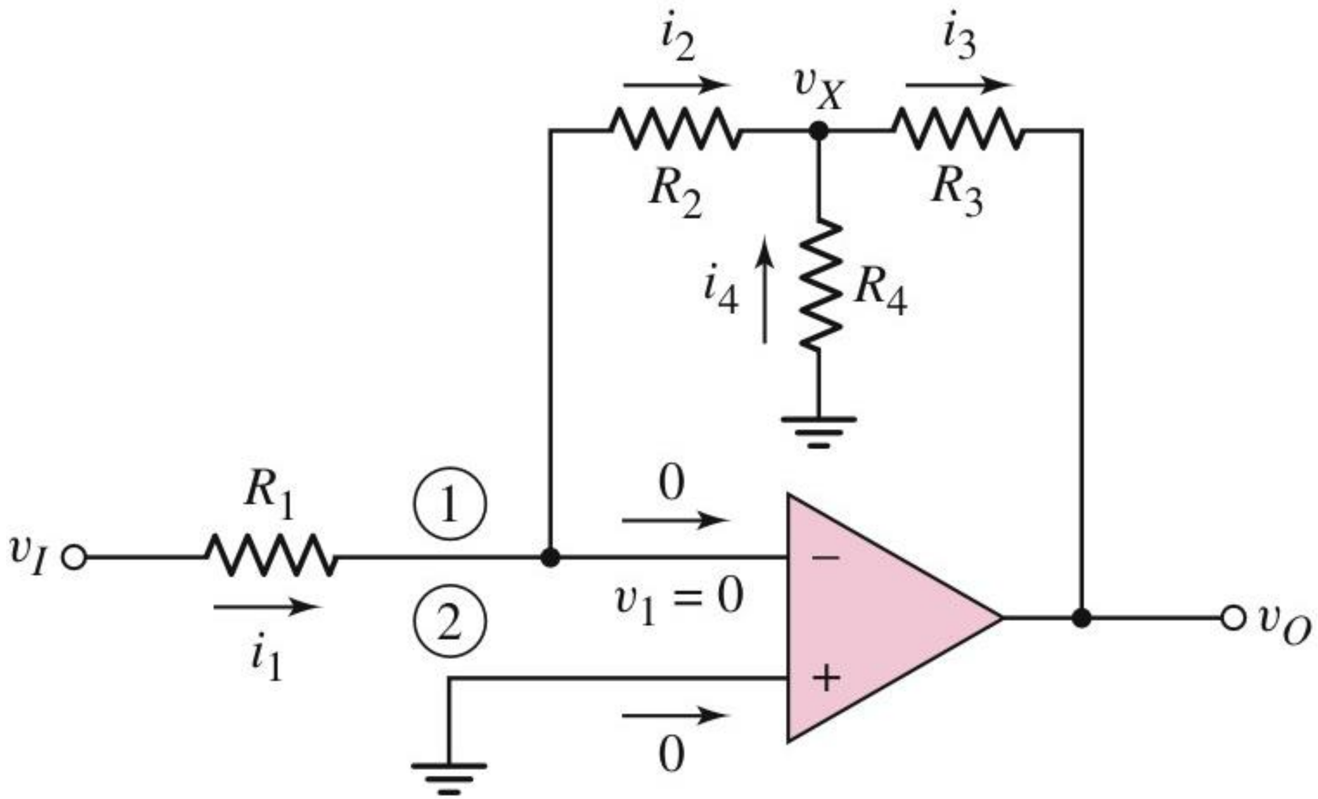
- A_v is known as closed loop gain
- Notice here that the voltage gain no longer depends on the op-amp, rather depends on the resistance.
- By varying the R_f/R_1 ratio we can get the desired voltage gain
- In this circuit, however, now the input resistance has reduced to R_1.

Inverting amplifier (using ideal op-amp)

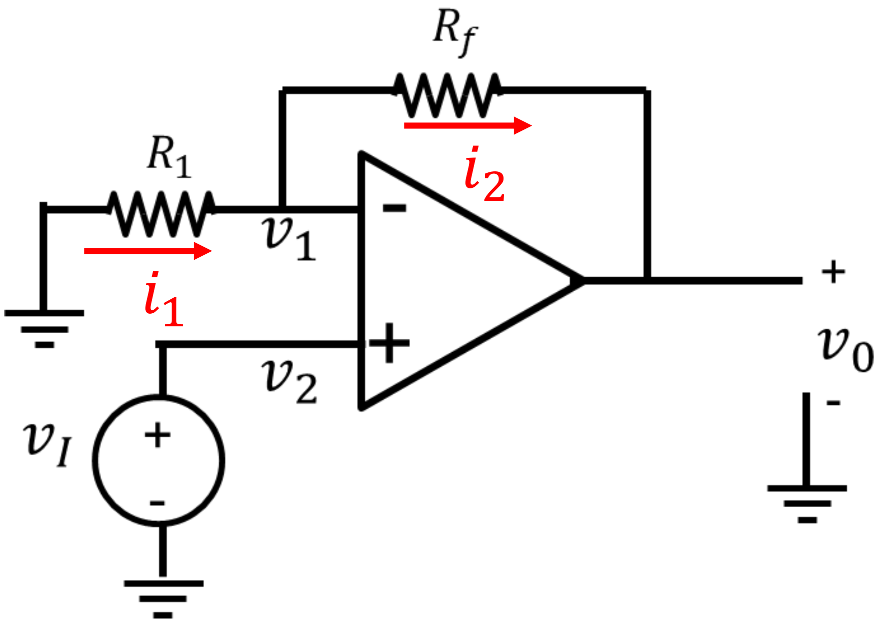
Problem: show that for the following network the voltage gain is

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

What are the input and output resistances?



Noninverting amplifier (using ideal op-amp)



- In a noninverting amplifier, the input signal is applied to the noninverting input terminal of the op-amp.
- Notice that the feedback is still applied to the inverting terminal, thus we still have a negative feedback system.
- Using virtual short concept we can write:

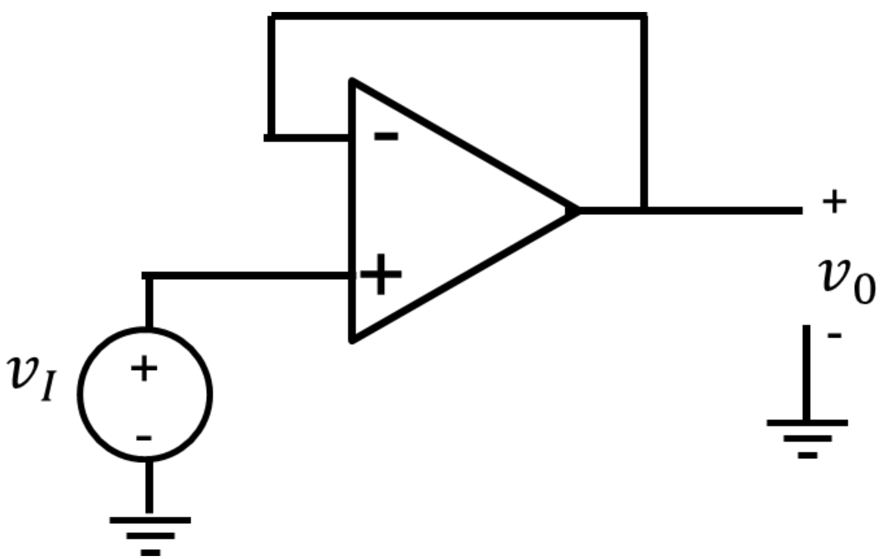
$$v_1 = v_2 = v_I$$

- The currents are: $i_1 = \frac{0-v_I}{R_1} = -\frac{v_I}{R_1}$ and $i_2 = \frac{v_I-v_o}{R_f}$
- $i_1 = i_2$
- Therefore the voltage gain is:

$$A_v = \frac{v_o}{v_I} = \left(1 + \frac{R_f}{R_1}\right)$$

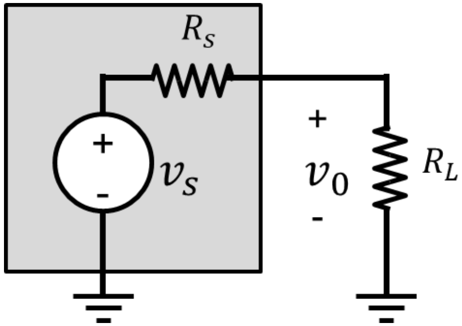
Voltage follower

- For a noninverting op-amp we saw that the gain becomes: $A_v = \frac{v_o}{v_I} = \left(1 + \frac{R_f}{R_1}\right)$.
- If we now remove the resistance R_1 (i.e. $R_1 = \infty$), $A_v = 1$, for any value of R_f except ∞.
- i.e. as long as there exist a feedback, $A_v = 1$. so we can replace R_f with a short circuit.
- This circuit is called a voltage follower as it replicates the input signal at the output without any amplification or phase change.
- a voltage follower is also called a unity-gain amplifier, a buffer amplifier, and an isolation amplifier



Use of voltage follower

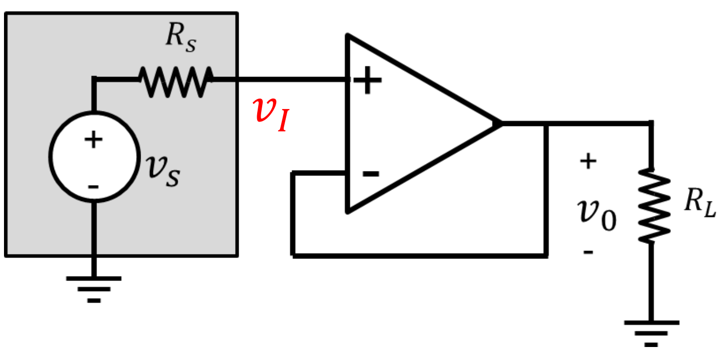
Consider the following circuit where a real voltage source with finite series resistance is connected to a load resistance



$$v_o = \frac{R_L}{R_L + R_s}$$

- The voltage seen by the load resistance depends on the value of the load resistance.
- If RL becomes comparable to R_s, then the voltage across R_L can be significantly less than the rated voltage of the source.

Now lets add a voltage follower circuit in between the source and the load



- Since the input resistance of the op-amp is ∞

$$v_o = v_I = v_s$$

- Since the output resistance $R_o = 0$,

v_o remains equal to v_s irrespective of the value of the load resistance.

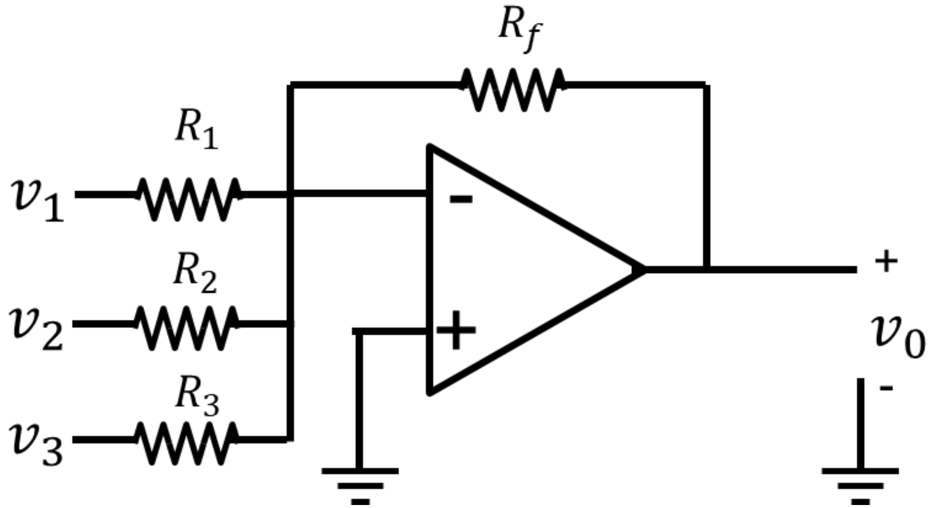
- That means, by using a voltage follower we have eliminated the *loading effect* on the voltage source.

Summing amplifier (using ideal op-amp)

Problem: show that for the following network the output voltage is

$$v_o = -\left(\frac{R_f}{R_1}v_1 + \frac{R_f}{R_2}v_2 + \frac{R_f}{R_3}v_3\right)$$

[*Hint: use the principle of superposition*]



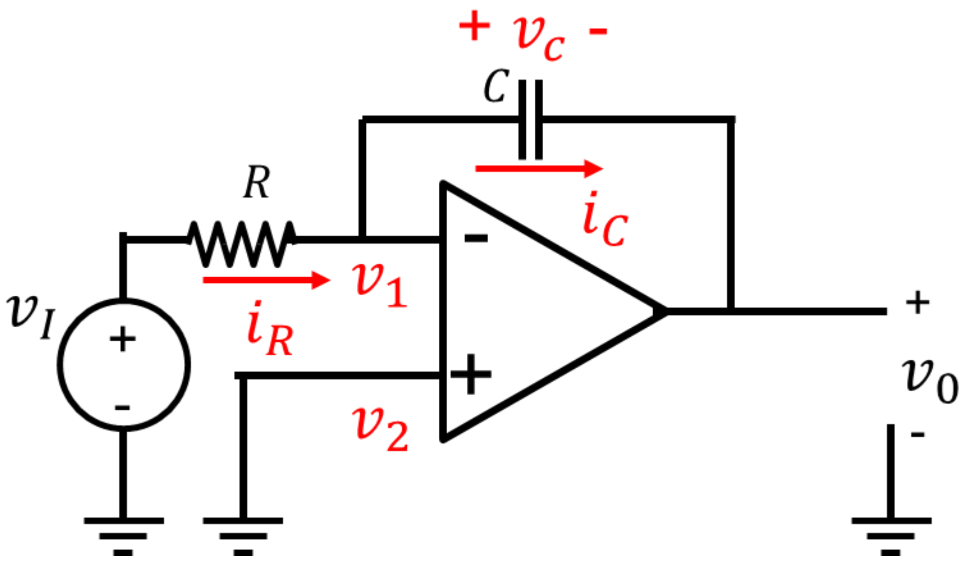
If we now choose

$R_f = R_1 + R_2 + R_3$

$v_o = -(v_1 + v_2 + v_3)$

i.e. v_o simply becomes an inverted sum of v_1, v_2 and v_3.

Op-amp as an integrator (using ideal op-amp)



- From the circuit, we get:

$$i_R = \frac{v_I}{R}$$

$$i_C = C\frac{dv_C}{dt} = C\frac{d(v_1 - v_o)}{dt} = -C\frac{dv_o}{dt}$$

- Since $i_C = i_R$

$$\frac{v_I}{R} = -C\frac{dv_o}{dt}$$

Or

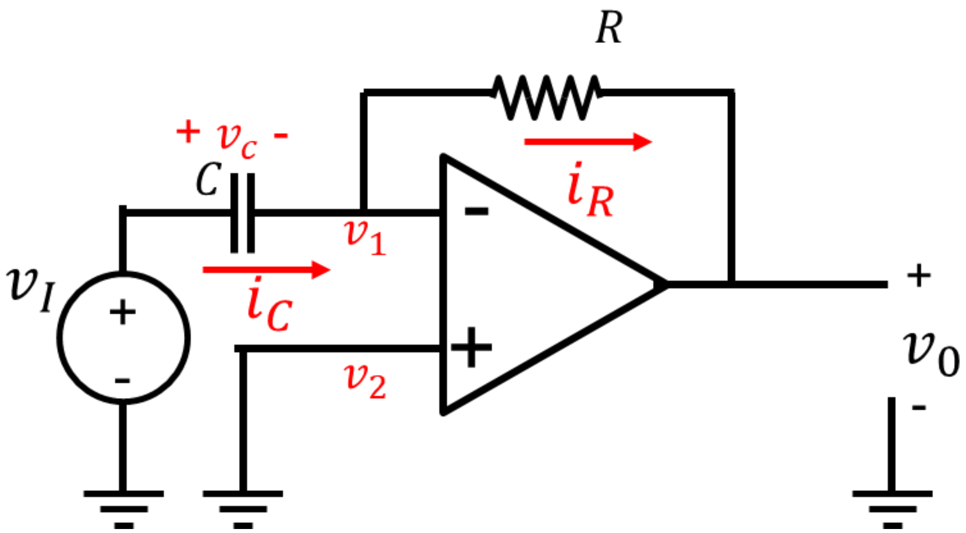
$$dv_o = -\frac{1}{RC}v_I dt$$

Or

$$v_o = -\frac{1}{RC}\int_0^t v_I dt' + V_C$$

Where V_C is the initial stored charge in the capacitor

Op-amp as a differentiator (using ideal op-amp)



- From the circuit, we get:

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

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

- Since $i_C = i_R$

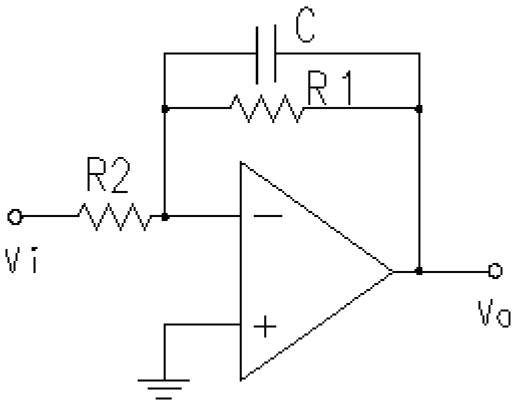
$$-\frac{v_o}{R} = C\frac{dv_I}{dt}$$

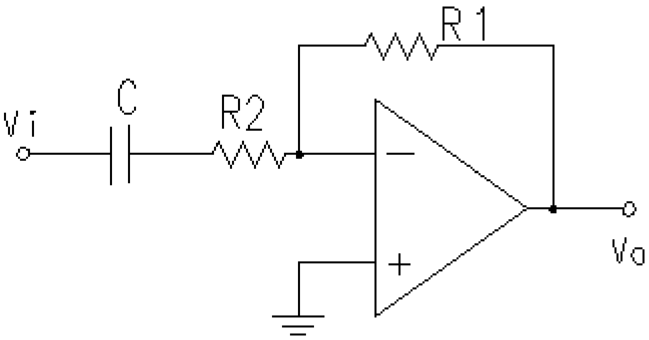
Or

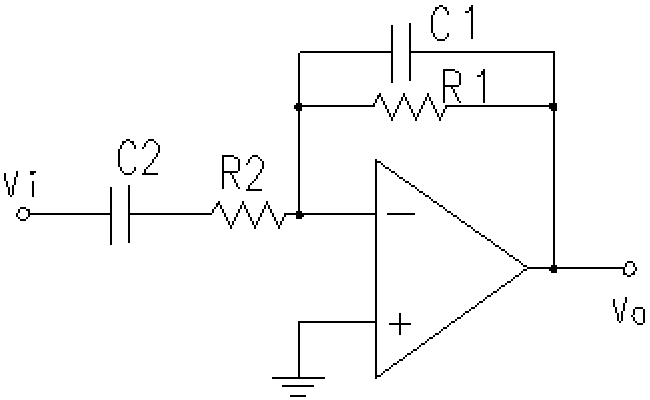
$$v_o = -RC\frac{dv_I}{dt}$$

Op-amp as a Filters(using ideal op-amp)

Problem: Find the $|v_o/v_i|$ for the following circuits and which type of filter do they represent?







Non-ideal op-amp

- So far our discussion has been restricted to ideal op-amps only. For ideal op-amp we have seen, the output only depends on the difference between the two inputs.

$$v_0 = A_{od}(v_2 - v_1)$$

If both the inputs are equal, i.e. $v_2 = v_1$, the op-amp output is zero.

- However, practical op-amps not only amplifies the difference between the two input signals, but also their summation.
- So a more general expression for the output voltage is given as:

$$v_0 = A_{od}(v_2 - v_1) + A_{cm}\frac{(v_2 + v_1)}{2}$$

- Here you can notice that the output voltage does not go to zero even when $v_2 = v_1$.
- In this expression:
  - $(v_2 - v_1) = v_d$ stand for differential voltage
  - $\frac{(v_2+v_1)}{2} = v_{cm}$ stand for common mode voltage
  - A_{od} stands for differential mode gain
  - A_{cm} stands for common mode gain
- Typically common mode gain A_{cm} is much smaller than the differential mode gain.
- The ratio between the differential mode gain and common mode gain is known as '*common mode rejection ratio*' (CMRR) and expressed as:

$$CMRR = \left|\frac{A_{od}}{A_{cm}}\right|$$

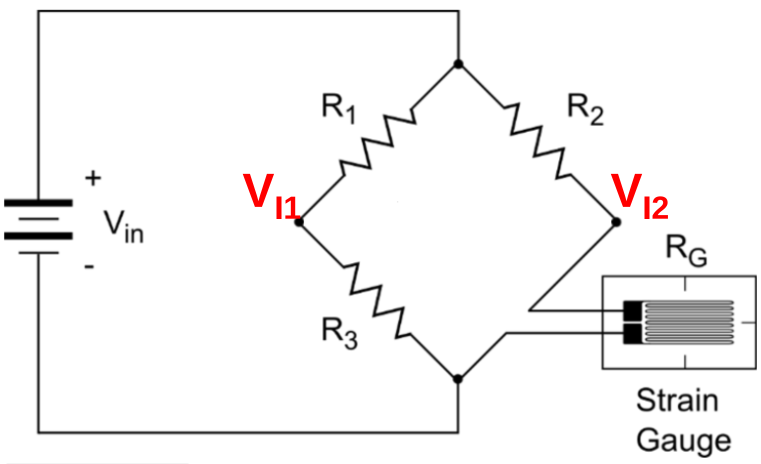
- CMRR is usually expressed in dB

$$CMRR(dB) = 20log_{10}\left|\frac{A_{od}}{A_{cm}}\right|$$

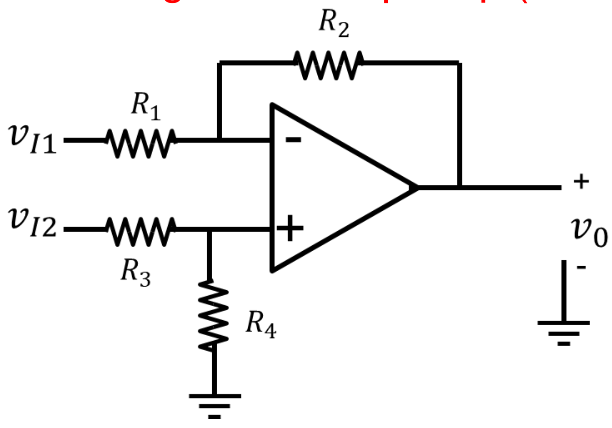
- For an ideal op-amp CMRR = ∞, practical op-amp has CMRR in the range of 80-90dB.

Difference amplifier (using ideal op-amp)

A difference amplifier is used to measure the difference between two signals. Let's understand this with a practical example. Following is a circuit of a strain gauge using a Wheatstone bridge. A strain gauge is a device used to measure strain on an object by sensing the change in resistance (R_G). In a Wheatstone bridge, when $R_1/R_3 = R_2/R_G$, the voltages V_1 and V_2 becomes equal. Any deviation from this equilibrium, $|V_{I1}-V_{I2}|$ becomes nonzero. By sensing this voltage change the change in resistance in the strain gauge and change in the specimen can be detected. Now in order to amplify this differential voltage an op-amp based difference amplifier can be used.

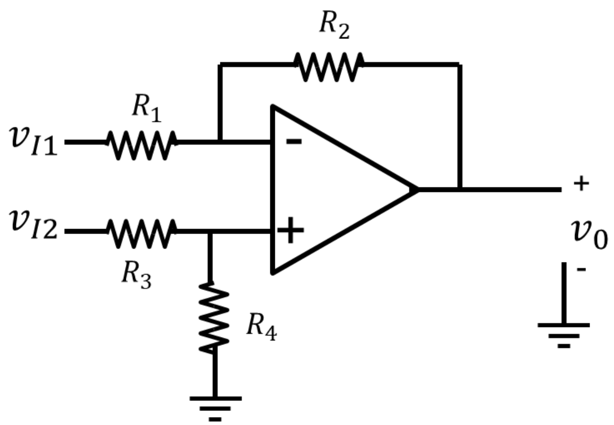


Although we can simply use an op-amp for this job, but since the gain of an om-amp is very high we would prefer to use the op-amp in a negative feedback circuit configuration. The circuit is shown below. Here, remember we are using an ideal op-amp (CMRR = ∞).



Difference amplifier (using ideal op-amp)

For the circuit, the output voltage can be expressed as:



$$v_o = \left(1 + \frac{R_2}{R_1}\right)\left(\frac{\frac{R_4}{R_3}}{1 + \frac{R_4}{R_3}}\right) v_{I2} - \frac{R_2}{R_1} v_{I1}$$

Lets express v_{I1} and v_{I2} in terms of two voltages v_d and v_{cm} as:

$$v_d = (v_{I2} - v_{I1})$$

and

$$v_{cm} = \frac{(v_2 + v_1)}{2}$$

And also for simplicity lets denote $\frac{R_2}{R_1} \equiv a$ and $\frac{R_4}{R_3} \equiv b$.

If we now put these values in the expression of v_o, we get:

$$v_o = \left[(1 + a)\left(\frac{b}{1 + b}\right) - a\right] v_{cm} + \frac{1}{2}\left[(1 + a)\left(\frac{b}{1 + b}\right) + a\right] v_d$$

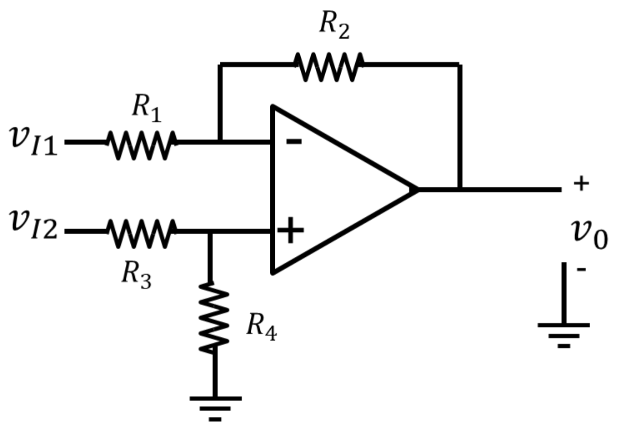
If you observe closely, $\left[(1 + a)\left(\frac{b}{1+b}\right) - a\right]$ represents the common mode gain (A_{cm}) and $\frac{1}{2}\left[(1 + a)\left(\frac{b}{1+b}\right) + a\right]$ represents the difference mode gain (A_d) of the overall circuit.

Derive these expressions

Difference amplifier (using ideal op-amp)

Therefore:

$$v_o = A_{cm}v_{cm} + A_d v_d$$



Notice here that even though we used an ideal op-amp in this circuit which has CMRR = ∞, because of the various resistors we may get finite CMRR.

The condition for CMRR = ∞ in this circuit will be when A_{cm} becomes 0.

i.e.

$$\left[(1+a)\left(\frac{b}{1+b}\right) - a\right] = 0$$

or

$$\frac{a}{1+a} = \frac{b}{1+b}$$

i.e.

$$a = b$$

or

$$\frac{R_2}{R_1} = \frac{R_4}{R_3}$$

Problem: calculate the CMRR of a difference amplifier with $\frac{R_2}{R_1} = 10$ and $\frac{R_4}{R_3} = 11$.