

EE Dept, IIT Bombay

Academic Year: 2024-2025, Semester II (Spring)

Course: MS101 Makerspace

EE Lectures 3 & 4

Operational Amplifier Circuits

Topics: (i) signal basics, (ii) amplifiers, (iii) feedback amplifiers, (iv) op amps, (v) linear circuits, (vi) practical op amp, (vii) non-inverting amplifier analysis as a feedback amplifier, (viii) voltage comparators.

Reference: AS Sedra, KC Smith, TC Carusone, & V Gaudet, Microelectronic Circuits, 8th ed., Oxford University Press, 2020. Chs. 1, 2, 11, 13, 15.

1. Signal Basics

Signal: A function (waveform) conveying information (resolution of uncertainty about a phenomenon of interest).

Test signal: Function (usually deterministic) for characterizing a system.

Electric signal: Time-varying voltage or current waveform on a port (2 terminals or a pair of conductors).

Noise: A disturbance unrelated to the signal.

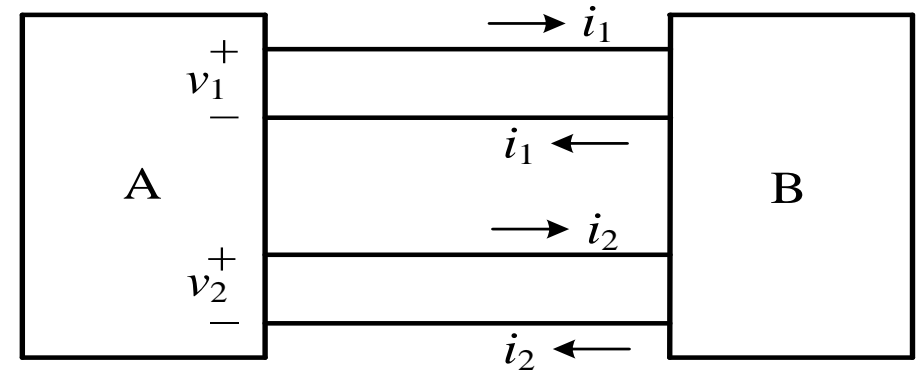
Distortion: A disturbance related to the signal.

Differential signals: Each signal needs two conductors.

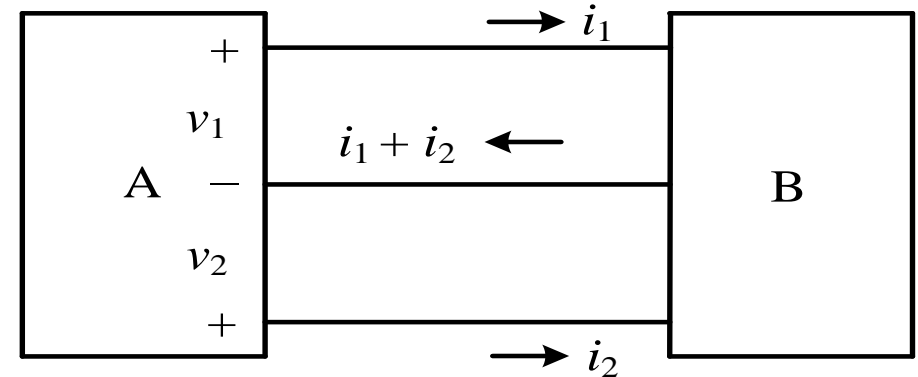
Single-ended signals: Several signals share a common reference in the case of voltage signals, & a common return in the case of current signals.

Circuit ground: A conductor or terminal (usually attached to a power supply terminal) serving as the common reference for several voltages or the common return path for several currents.

Grounded signals: Single-ended signals with circuit ground as the reference. These signals are preferred over differential signals, as they need fewer conductors and require simpler circuits. Ground interconnection is usually not explicitly shown in circuit diagrams.



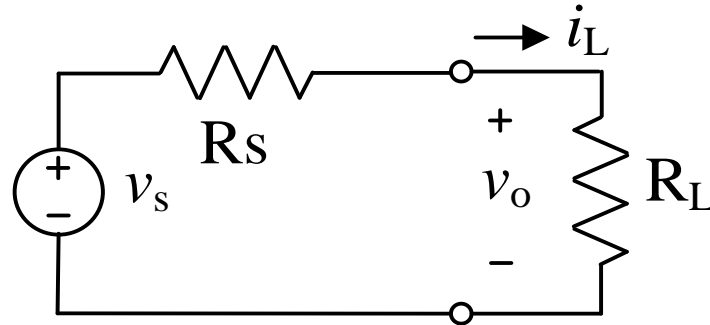
Two differential signals (each with two conductor)



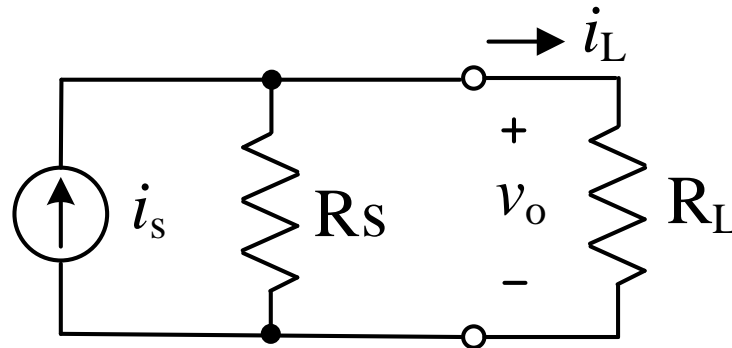
Two single-ended signals (common reference & return)

Two signal representations

Voltage source
model (Thevenin
form)



Current source
model (Norton
form)



Preferred representation

Voltage source, if $R_s \ll R_L$. Current source, if $R_s \gg R_L$.

Ideal voltage source: $R_s = 0$. Ideal current source: $R_s = \infty$.

$$i_L = \frac{v_s}{R_s + R_L}$$

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

$$v_o \approx v_s, \quad R_L \gg R_s$$

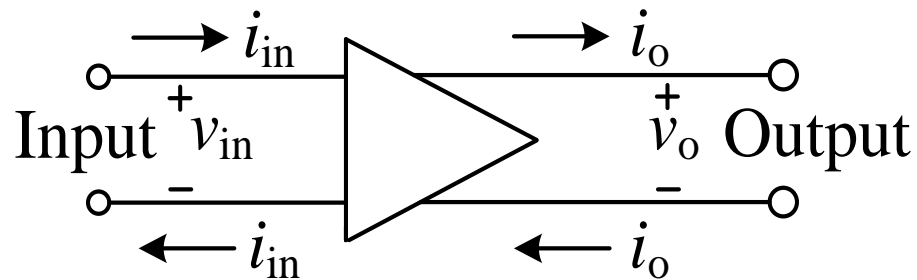
$$v_o = i_s \left(\frac{R_s R_L}{R_s + R_L} \right)$$

$$i_L = \frac{v_o}{R_L} = i_s \left(\frac{R_s}{R_s + R_L} \right)$$

$$i_L \approx i_s, \quad R_L \ll R_s$$

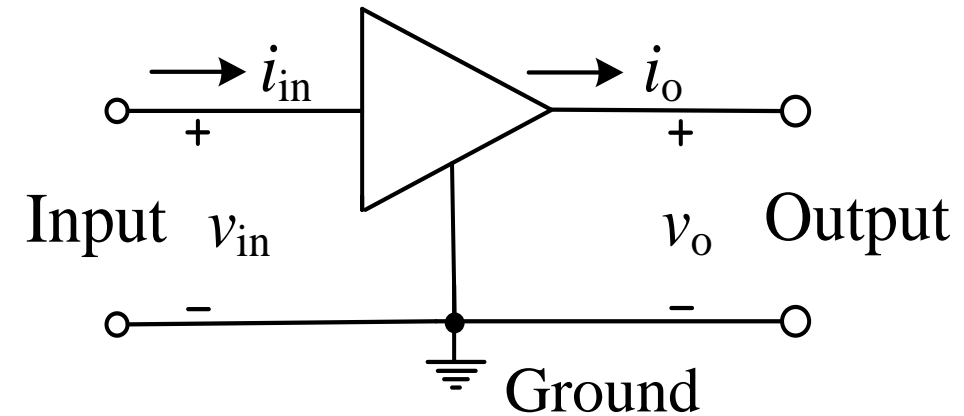
2. Amplifiers

Amplifier: A circuit or device for increasing the power of the input signal(s) using the power from dc source(s).



Amplifier with differential input & differential output

- Voltage gain $A_v = v_o / v_{in}$.
 - Amplification: $A_p > 1$.
 - An amplifier may have multiple inputs and multiple outputs.
- Current gain $A_i = i_o / i_{in}$.
Attenuation: $A_p < 1$.



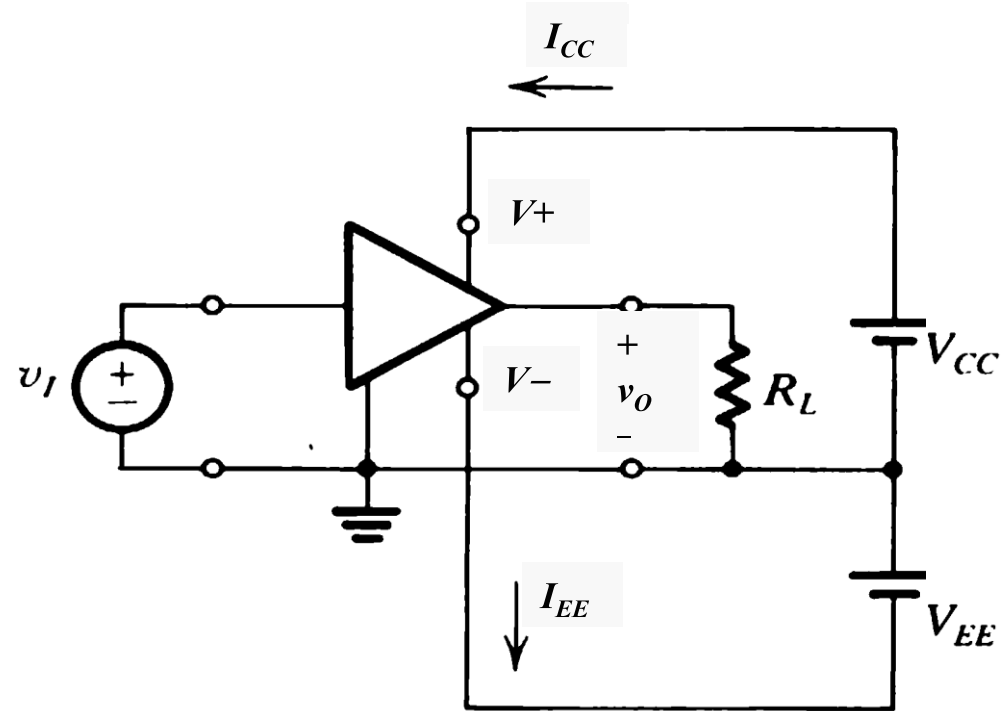
Amplifier with grounded input & grounded output

$$\text{Power gain } A_p = (v_o i_o) / (v_{in} i_{in}) = A_v A_i.$$

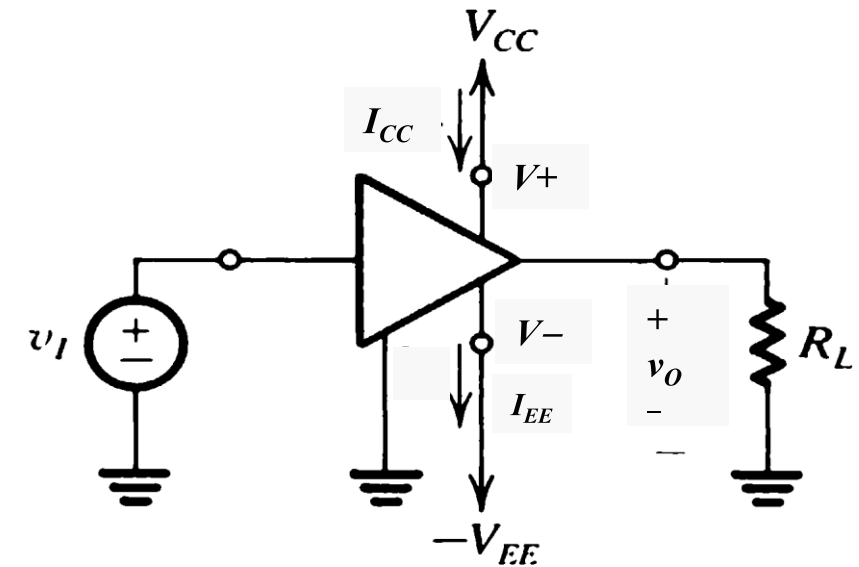
Amplifier power supplies

An amplifier delivers more power to the output load than it draws from the input source. It needs dc power sources for the extra power delivered to the load as well as any power dissipated in the internal circuit.

- Dual supply amplifier: +ve & -ve dc supplies are connected to the circuit ground. Supplies need not be equal.
- Single supply amplifier: One of the two supply terminals is connected to the circuit ground.
- DC power consumption
$$P_{dc} = V_{CC}I_{CC} + V_{EE}I_{EE}$$
- Input & output voltage swings are limited by the circuit & supply voltages.



(a) Circuit diagram with explicit connections.



(b) Circuit diagram, with the circuit ground as the common reference for all voltages.

Four types of single-ended amplifiers modeled as dependent sources

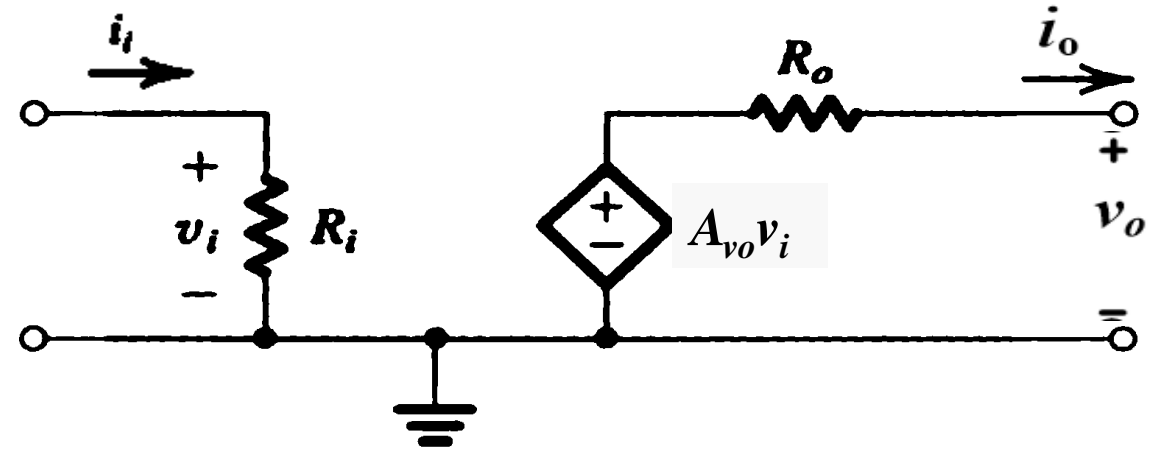
i) Voltage amplifier

(voltage input, voltage output)

Model: Voltage-controlled voltage source (VCVS)

Open-circuit voltage gain: A_{vo}

Ideal VCVS: $R_i = \infty$, $R_o = 0$



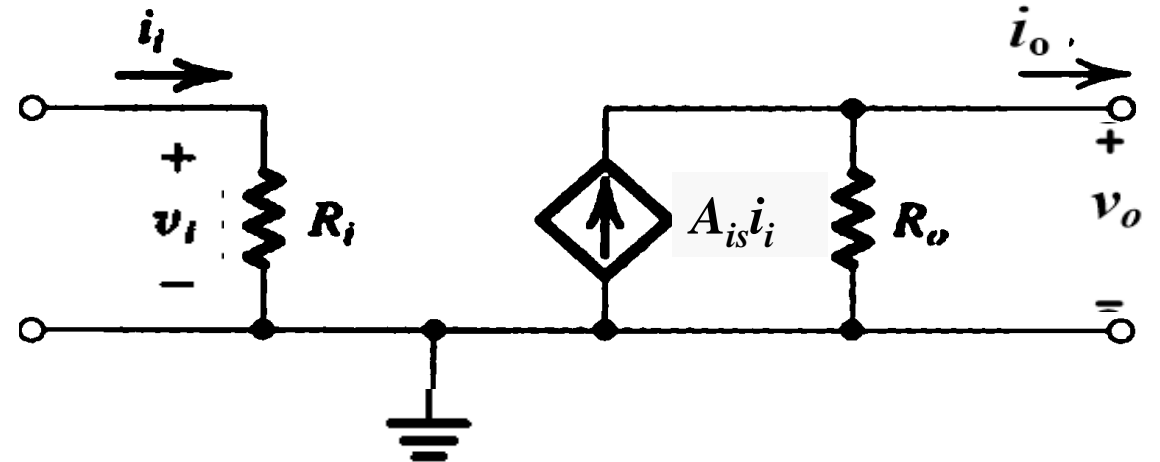
ii) Current amplifier

(current input, current output)

Model: Current-controlled current source (CCCS)

Short-circuit current gain: A_{is}

Ideal CCCS: $R_i = 0$, $R_o = \infty$



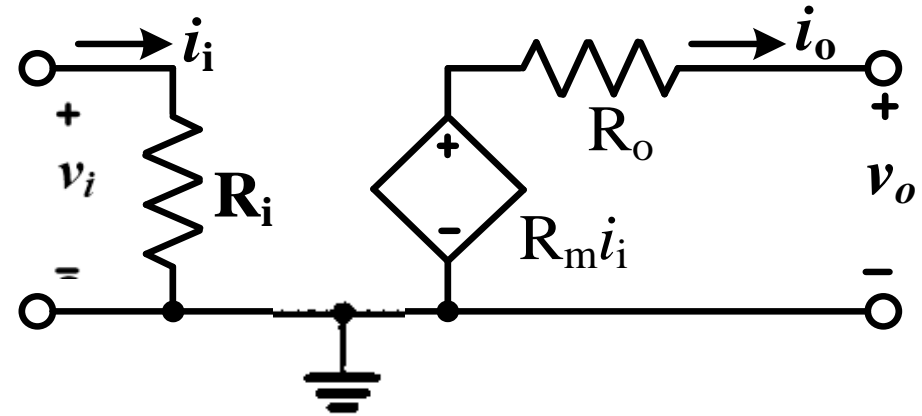
iii) Trans-resistance amplifier

(current input, voltage output)

Model: Current-controlled voltage source (CCVS)

Open-circuit trans-resistance: R_m

Ideal CCVS: $R_i = 0$, $R_o = 0$



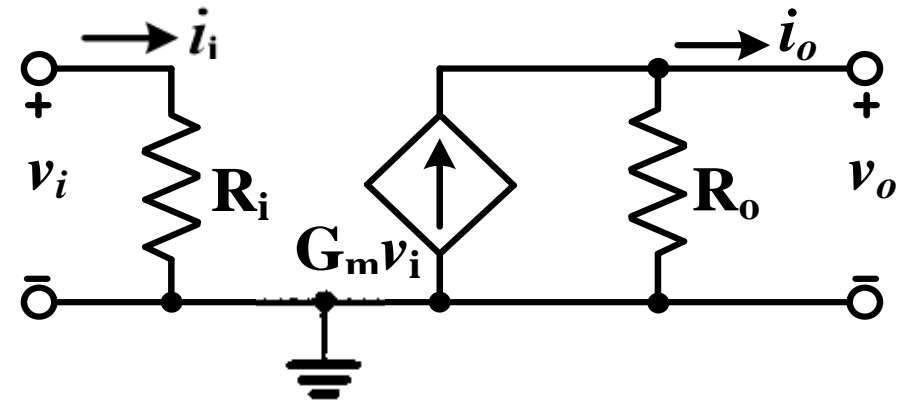
iv) Trans-conductance amplifier

(voltage input, current output)

Model: Voltage-controlled current source (VCCS)

Short-circuit trans-conductance: G_m

Ideal VCCS: $R_i = \infty$, $R_o = \infty$



Differential signals

- A differential signal has two voltages with ground as the reference. The information is carried by the difference between the two voltages.

- It is shown as two voltages (v_1 , v_2). It can be modeled using a common-mode (CM) voltage and a differential-mode (DM) voltage.

- Terminal voltages: v_1 & v_2

- We define:

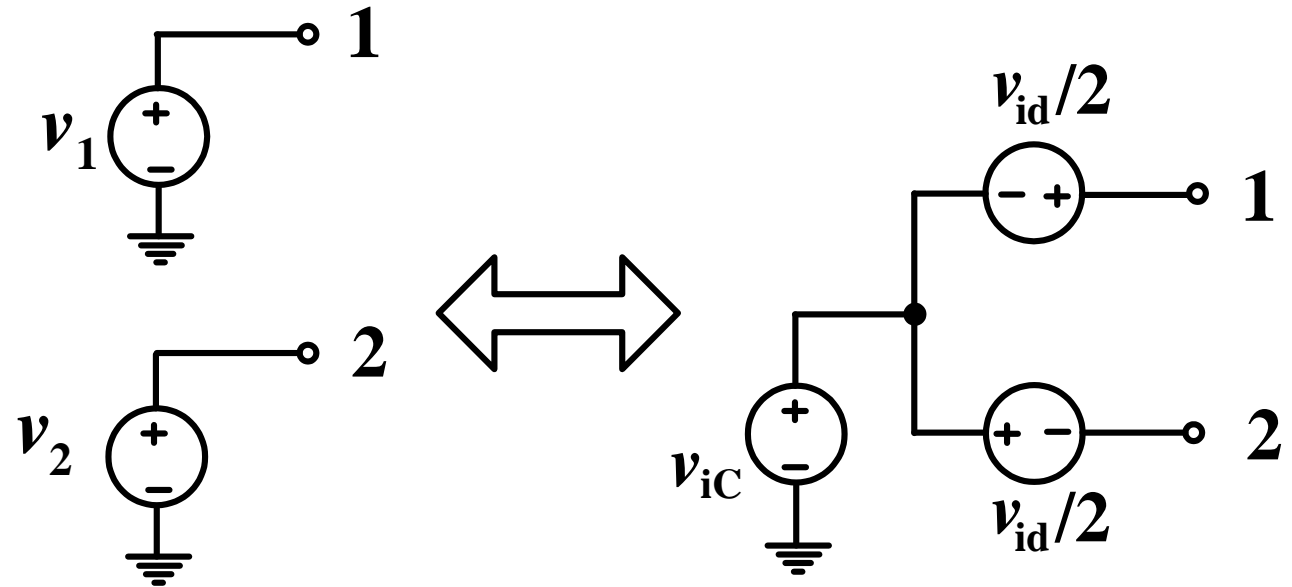
Common-mode (CM) voltage: $v_{ic} = (v_1 + v_2)/2$

Differential-mode (DM) voltage: $v_{id} = v_1 - v_2$

- Terminal voltages from the DM & CM voltages:

$$v_1 = v_{ic} + v_{id}/2$$

$$v_2 = v_{ic} - v_{id}/2$$



Differential signal example: Wheatstone bridge balance detection

The bridge with matched R_1 and R_2 is used to detect mismatch between R_3 & R_4 . Excitation voltage: v_x . Output voltages: v_1 , v_2 .

$$\text{Let } R_1 = R_2 \Rightarrow v_1 = \frac{R_2}{R_1 + R_2} v_x = \frac{v_x}{2}, \quad v_2 = \frac{R_4}{R_3 + R_4} v_x$$

CM voltage $v_{ic} = (v_1 + v_2)/2$. DM voltage $v_{id} = v_1 - v_2$.

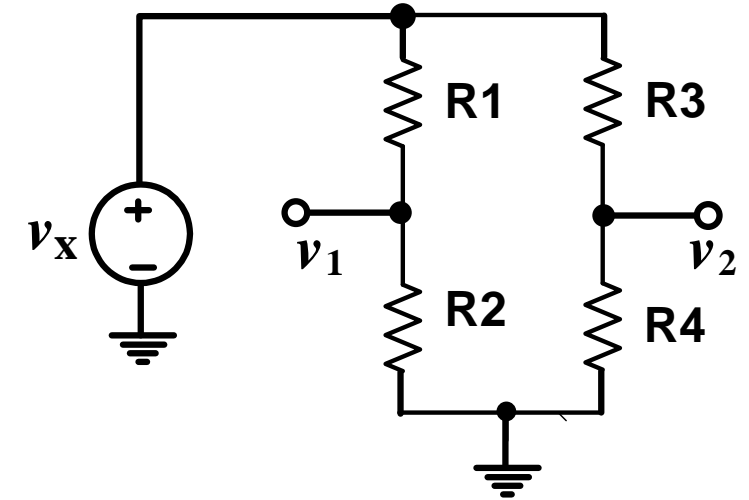
i) Balanced bridge, $R_3 = R_4$, $v_1 = v_2 = v_x/2$.

$$v_{ic} = \frac{v_1 + v_2}{2} = \frac{v_x}{2}, \quad v_{id} = v_1 - v_2 = 0.$$

ii) Unbalanced bridge, $R_3 \neq R_4$. Say $R_3 = R_4(1+\delta) \Rightarrow v_1 = \frac{v_x}{2}$ & $v_2 = \frac{R_4}{R_4(1+\delta) + R_4} v_x = \frac{v_x}{2+\delta}$

$$v_{ic} = \frac{v_1 + v_2}{2} = \frac{v_x}{2} \frac{1+\delta/4}{1+\delta/2} \approx \left(1 - \frac{\delta}{4}\right) \frac{v_x}{2}, \quad v_{id} = v_1 - v_2 = \frac{v_x}{2} \frac{\delta/2}{1+\delta/2} \approx \frac{\delta}{4} v_x$$

So the CM voltage is substantial and the DM voltage is very small. $v_{id}/v_{ic} \approx \delta/2$. We need to use a differential amplifier that takes v_1 & v_2 as inputs, and amplifies the small DM voltage while rejecting the large CM voltage.



Differential amplifier

- Differential input voltage & single-ended output voltage
- Used to amplify the DM voltage while rejecting the CM voltage.

DM input voltage: $v_{id} = v_1 - v_2$

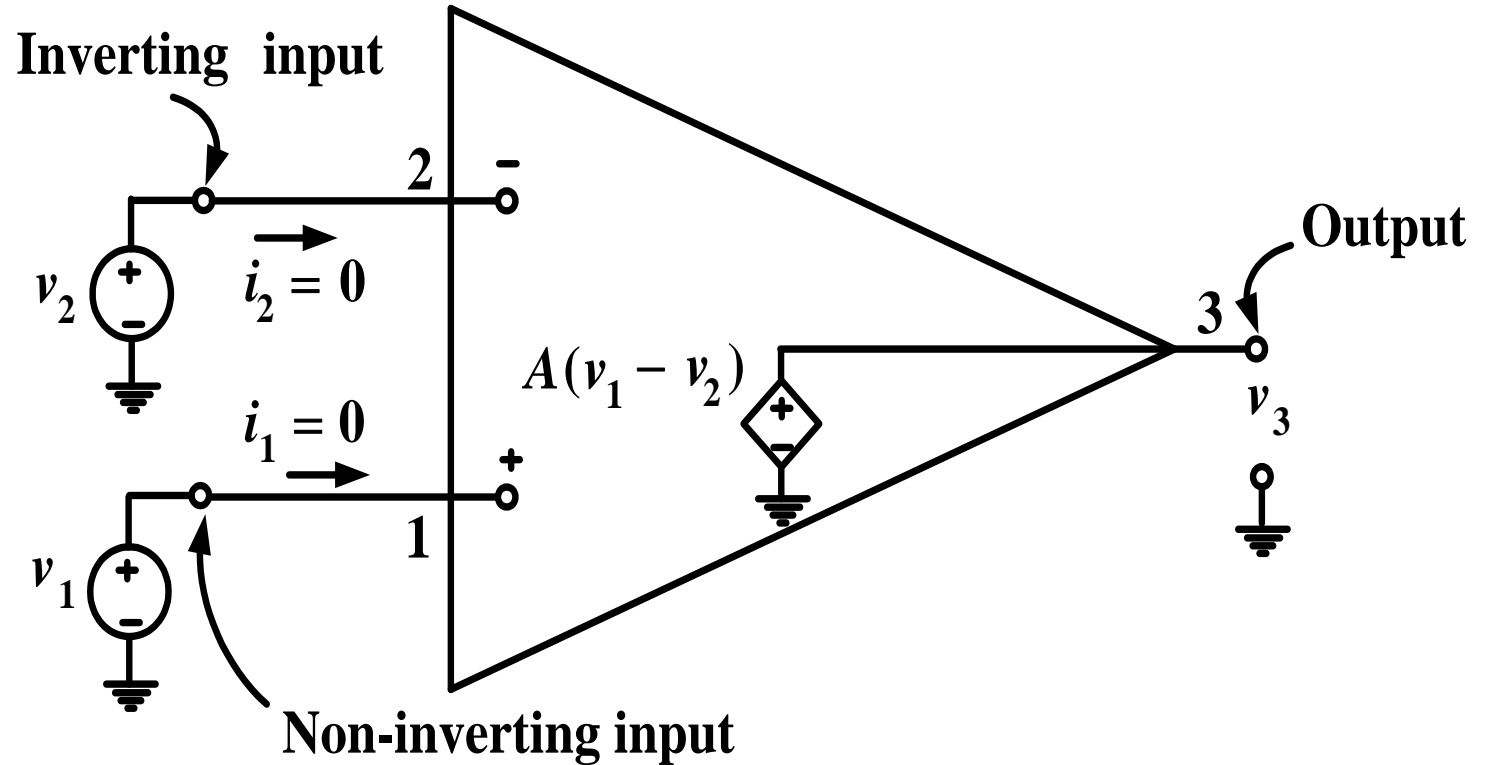
CM input voltage: $v_{ic} = (v_1 + v_2)/2$

$v_1 = v_{ic} + v_{id}/2$; $v_2 = v_{ic} - v_{id}/2$

Ideal differential amplifier

- Zero input currents.
- Amplifies the DM input voltage.
- Rejects the CM input voltage.
- Single-ended output voltage:

$$v_3 = A v_{id}$$

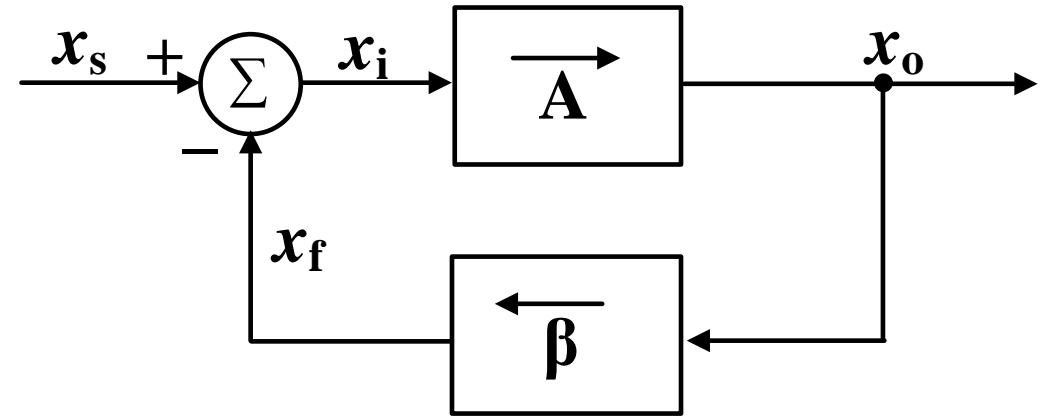


3. Feedback Amplifiers

- **Feedback:** Addition of a fraction of the output to the input for desirable circuit behavior.
- **Negative feedback:** The output fraction opposes the input. It is used in amplifiers to
 - desensitize the gain, making it less sensitive to the circuit component parameters;
 - extend the bandwidth.;
 - control the input and output resistances: raise or lower R_{in} and R_o by appropriate feedback topology.The desirable properties are obtained at the expense of gain reduction.
- **Positive feedback:** The output fraction increases the input. It is used to realize oscillators (function generators) & bi-stable circuits.
- **Negative & positive feedback combination:** It is used in filters (circuits with specific frequency response) for signal processing.

Feedback amplifier

- Signal-flow diagram: input x_s , output x_o (voltage or current).
- Amplifier: input x_i , open-loop gain A , output x_o .
- Feedback network: input x_o , feedback factor β , feedback signal x_f .
- Adder: inputs x_s & x_f , output: x_i).



$$x_f = \beta x_o. \quad x_i = x_s - x_f. \quad x_o = Ax_i = A(x_s - \beta x_o) \Rightarrow x_o(1 + A\beta) = Ax_s \Rightarrow x_o = Ax_s / (1 + A\beta).$$

- Feedback amplifier gain (closed-loop gain) $A_f = \frac{x_o}{x_s} = \frac{A}{1 + A\beta}$. For $A\beta \gg 1$, $A_f \approx \frac{1}{\beta}$.
- A may have large variability due to electronic device parameters. The circuit can be designed such that β depends only on passive components and thus has a precise value. Example: $A = 10^3$ to 10^5 & $\beta = 1/10$.
(i) $A = 10^3 \Rightarrow A_f = 10^3 / (1 + 10^2) = 10 / (1 + 10^{-2}) = 9.900$. (ii) $A = 10^5 \Rightarrow A_f = 10^5 / (1 + 10^4) = 9.999$.
- For $A\beta \gg 1$, A_f can be precise despite variability in A .
- Negative feedback can be used for obtaining precise gain, but with much less gain.

4. Operational Amplifiers

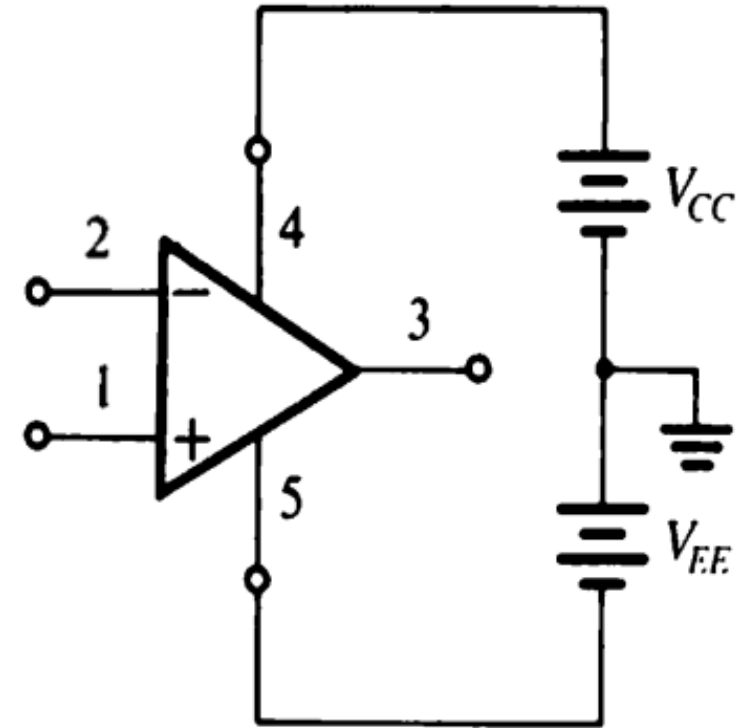
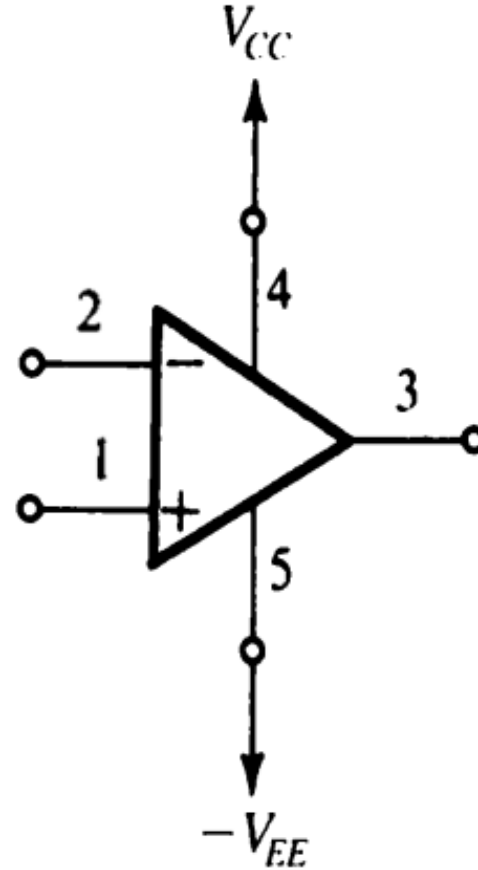
Operational amplifier (op amp, op-amp, or opamp)

It is a direct-coupled (dc) high-gain amplifier with differential voltage input & single-ended voltage output.

- Op amps were originally developed for mathematical operations on signal waveforms and are very convenient for designing circuits with feedback.
- Main objective: Circuit parameters should be determined by passive components & nearly independent of electronic device parameters.
- It is available as an integrated circuit (IC, electronic circuit with several internal passive & active devices on a single chip). Also available as several op amps on a single IC, or op amps with other circuits on the same IC.

Op amp power supplies

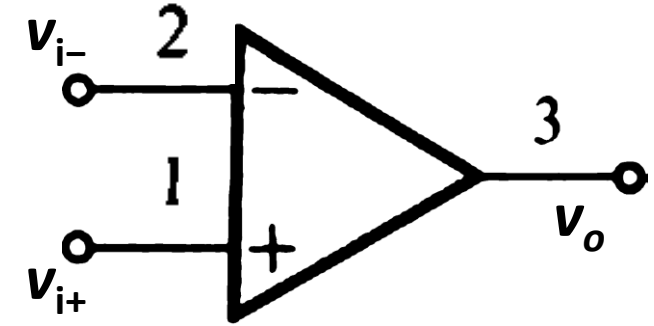
- The two supply terminals, for +ve & -ve supplies, may be labeled as V_{CC} & $-V_{EE}$; V_{CC+} & V_{CC-} ; V_+ & V_- ; or V_{DD} & V_{SS} .
- The supplies are shown connected to the circuit ground (Gnd) implicitly as in the left figure, or explicitly as in the right figure. The op amp itself does not have a Gnd terminal.
- The two supply voltages need not be equal. Many applications use single-supply circuits, with one of the two supply terminals connected to Gnd.



Op amp symbol & pin connections

- A simplified op amp symbol shows an amplifier with 3 terminals:

- non-inverting input terminal (1),
- inverting input terminal (2),
- output terminal (3).



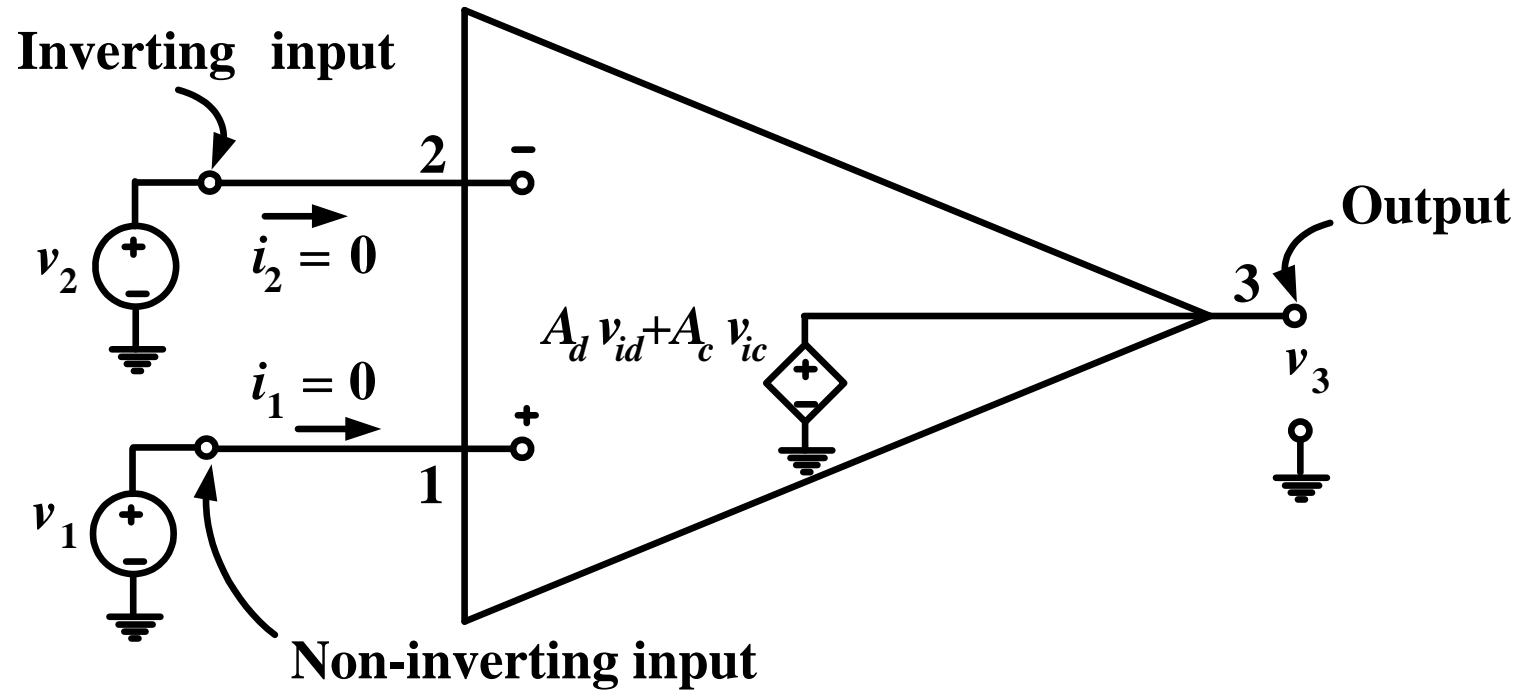
- The supply terminals are not shown in the simplified symbol. All terminal voltages are with reference to the circuit ground (Gnd), which is not shown in the symbol. The three terminals correspond to three single-ended ports:

- non-inverting input port v_{i+} : 1 – Gnd,
- inverting input port v_{i-} : 2 – Gnd,
- output port v_o : 3 – Gnd.

- An op amp needs at least 5 connection pins: two inputs, an output, and two supply pins.
- If an IC has multiple op amps, the supply pins may be shared. Minimum number of pins for an IC with 4 op amps (quad op-amp IC) = $3 \times 4 + 2 = 14$.
- Some op amps have additional pins for frequency compensation and offset nulling.

Input-output relation of an op amp

- Terminal voltages with reference to Gnd: inputs v_1 & v_2 , output v_3 .
- DM input: $v_{id} = v_1 - v_2$.
- CM input: $v_{ic} = (v_1 + v_2)/2$.
- Output voltage $v_3 = A_d v_{id} + A_c v_{ic}$, where A_d = DM gain, A_c = CM gain.
- Common-mode rejection ratio: $\text{CMRR} = A_d/A_c$.



Ideal op amp

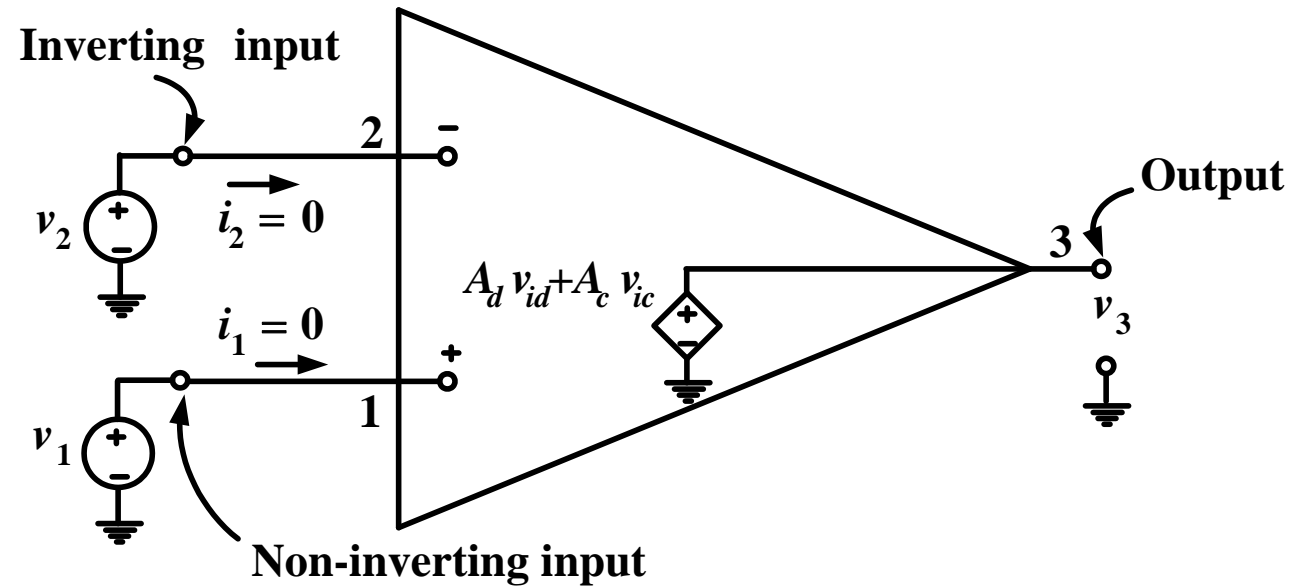
- $A_d \rightarrow \infty$. $A_c \rightarrow 0$. $v_3 = A_d(v_1 - v_2)$. $\text{CMRR} = A_d/A_c \rightarrow \infty$.
- DM input is amplified, with no effect of CM input on output. Required DM input $\rightarrow 0$ for finite output.
- Infinite input resistance for both inputs: zero input currents.
- Zero output resistance: output voltage unaffected by the load current.

Linear operation of an op amp

- For an op amp operating in its linear region,

$$v_3 = A_d v_{id} + A_c v_{ic}$$

For linear operation, the input and output voltages must be within the specified limits, which depend on the op amp type and the supply voltages.



- Ideally, $A_d \rightarrow \infty$, $A_c \rightarrow 0$. Then for finite v_3 , $v_{id} = v_3 / A_d \rightarrow 0$.

Also, input resistances R_{i1} , $R_{i2} \rightarrow \infty$, so the input currents $\rightarrow 0$.

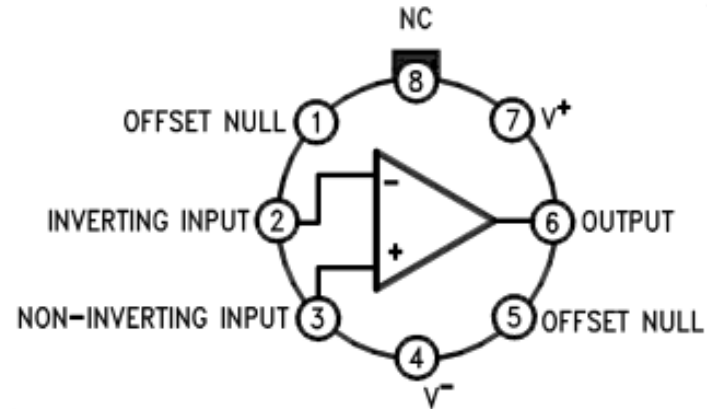
Thus, it appears as if the input terminals are shorted (since $v_{id} = 0$) with no current flow through them. This condition is known as a “virtual short” across the input terminals.

- Virtual short is a very useful concept in analyzing linear op amp circuits. It is applicable only during linear operation. The conditions for it are to be satisfied by external circuit & input voltages.
- During an op amp's nonlinear operation, the input currents may increase, and the output may be distorted.

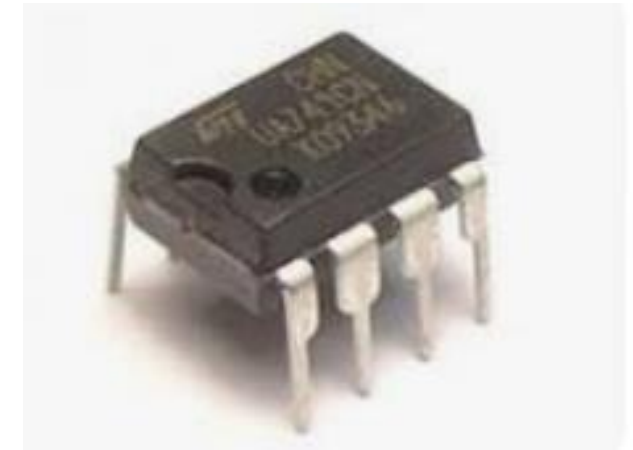
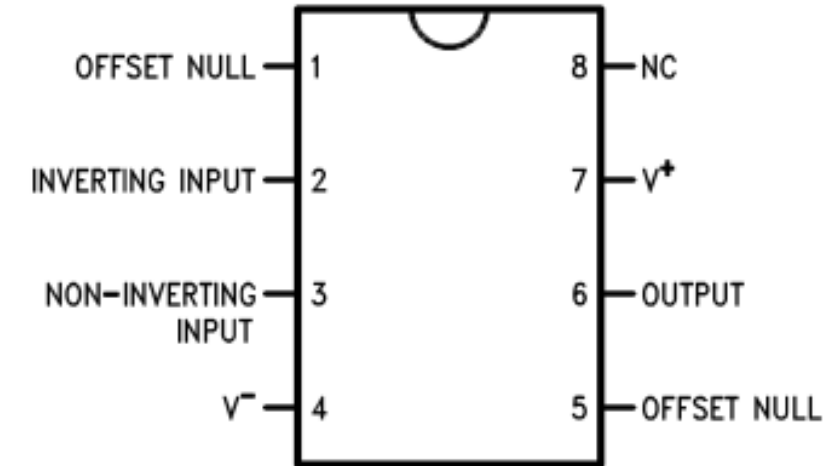
Op amp example: General-purpose op amp LM741

- Supply: $\pm 10\text{ V}$ to $\pm 18\text{ V}$, $\pm 15\text{ V}$ typical.
- $A_d > 50 \times 10^3$.
- For $\pm 15\text{ V}$ supply, Input range: $\pm 12\text{ V}$. Output swing: $\pm 12\text{ V}$.
- Output short-circuit current: 25 mA .
- Power consumption $< 100\text{ mW}$.

LMC Package
8-Pin TO-99
Top View



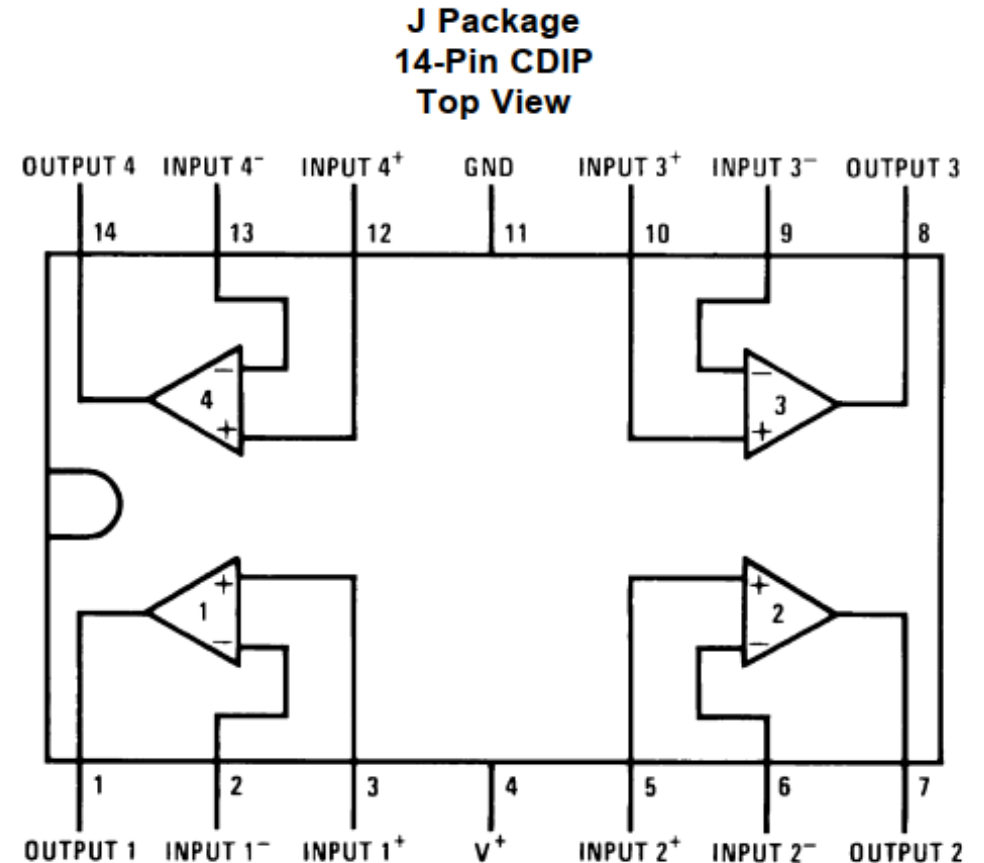
NAB Package
8-Pin CDIP or PDIP
Top View



Op amp example: Low-Power Quad Operational Amplifiers LM324

IC with 4 independent op amps and shared supply pins labelled as V+ & Gnd.

- Supply: $\pm 1.5\text{ V}$ to $\pm 16\text{ V}$, $\pm 2.5\text{ V}$ typical.
- $A_d > 50 \times 10^3$.
- For 2.5 V & -2.5 V supply (dual supply operation),
Input range: -2.5 V to 1 V . Output swing: -2.5 V to 1 V .
- For 5 V & Gnd supply (single supply operation),
Input range: 0 V to 3.5 V . Output swing: 0 V to 3.5 V .
- Output short-circuit current: 40 mA .
- Power consumption $< 15\text{ mW}$.



5. Linear Circuits

- Inverting Amplifier
- Non-inverting Amplifier
- Noninverting Unity Follower (Unity Buffer)
- Difference Amplifier
- Summing & Difference Amplifier
- Current-to-Voltage (I/V) Converter (Trans-resistance Amplifier)
- Voltage-to-Current (V/I) Converter (Trans-conductance Amplifier)
- Polarity-Controlled Amplifier
- AC Amplifiers (High-Pass Amplifiers)

5.1. Inverting Amplifier

Let us assume virtual short across the op amp inputs.

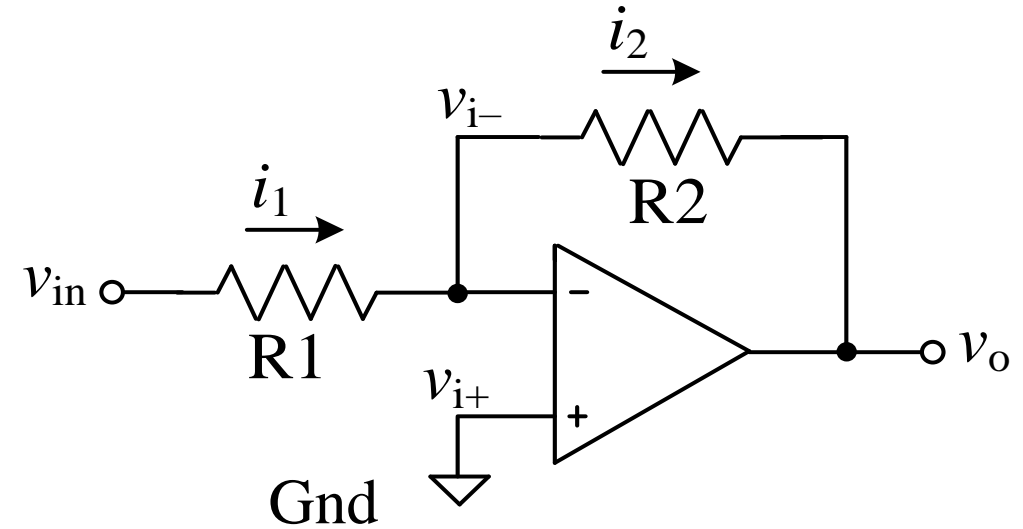
Virtual short: $v_{i-} = v_{i+}$ & $i_1 = i_2$.

$v_{i+} = 0$. $i_2 = i_1 = (v_{in} - v_{i-}) / R_1 = v_{in} / R_1$

$v_o = v_{i-} - R_2 i_2 = -(R_2 / R_1) v_{in}$

Voltage gain: $A_v = v_o / v_{in} = -R_2 / R_1$.

Input resistance: $R_{in} = v_{in} / i_1 = R_1$.



- R_{in} can be decreased by connecting a resistor between the input and the ground.
- Current & power gains depend on the load resistance (not shown).
- The circuit operation is based on negative feedback. Check the virtual short assumption for disturbance in v_{i-} .
 $v_{i-} \uparrow \rightarrow v_o \downarrow \rightarrow i_2 \uparrow \rightarrow v_{i-} \downarrow \Rightarrow$ virtual short is restored. Same with $v_{i-} \downarrow$.

It can be seen that the virtual short is violated if the input terminals are interchanged.

Hence, the virtual short is possible only for the input terminal polarities as shown in the figure.

- Application: Precise inverting gain with low to moderate R_{in}
- Example: $R_1 = 10 \text{ k}\Omega$, $R_2 = 100 \text{ k}\Omega$. $R_L = 1 \text{ k}\Omega$. $A_v = -10$, $R_{in} = 10 \text{ k}\Omega$.

5.2. Non-inverting Amplifier

$$V_{i+} = V_{in}$$

Virtual short assumption: $v_{i-} = v_{i+}$ & $i_1 = i_2$

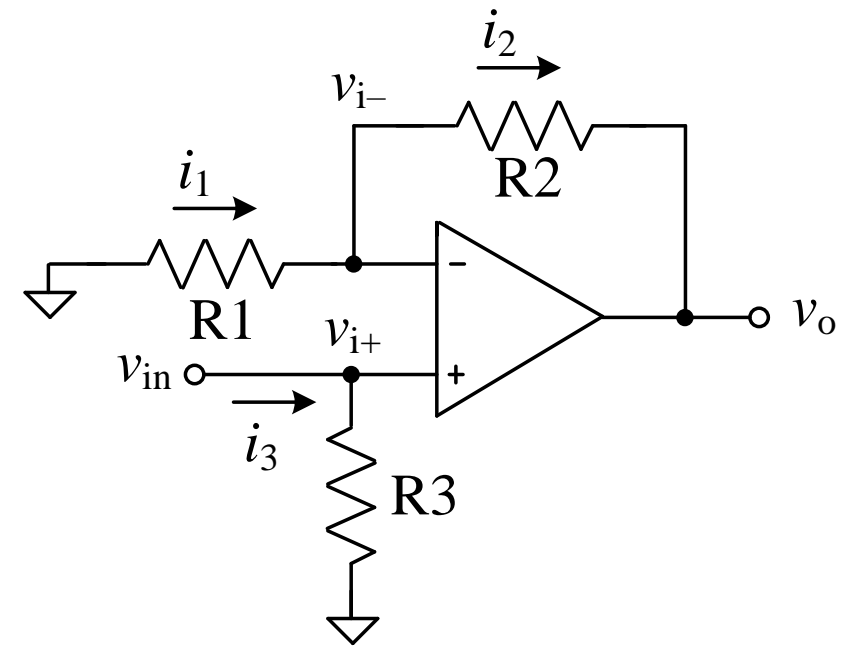
$$i_1 = (0 - v_{i-}) / R_1 = -v_{in} / R_1$$

$$v_o = v_{i+} - R_2 i_2 = (1 + R_2 / R_1) v_{in}$$

Voltage gain: $A_v = v_o / v_{in} = 1 + R_2 / R_1$

Input resistance: $R_{in} = v_{in} / i_3 = R_3$

- R3 is optional & selected for the desired R_{in} . Current & power gains depend on the load resistance (not shown).



- The circuit operation is based on negative feedback. Check the virtual short assumption for disturbance in v_{i-} .
 $v_{i-} \uparrow \rightarrow v_o \downarrow \rightarrow i_2 \uparrow \rightarrow v_{i-} \downarrow \Rightarrow$ virtual short is restored. Same with $v_{i-} \downarrow$.

It can be seen that the virtual short is violated if the input terminals are interchanged.

Hence, the virtual short is possible only for the input terminal polarities as shown in the figure.

- *Application:* Precise noninverting gain with high, moderate, or low R_{in} .
- Example: $R_1 = 10 \text{ k}\Omega$, $R_2 = 100 \text{ k}\Omega$, $R_3 = 1 \text{ M}\Omega$, $A_v = 11$, $R_{in} = 1 \text{ M}\Omega$.

5.3. Non-inverting Unity Follower (Unity Buffer)

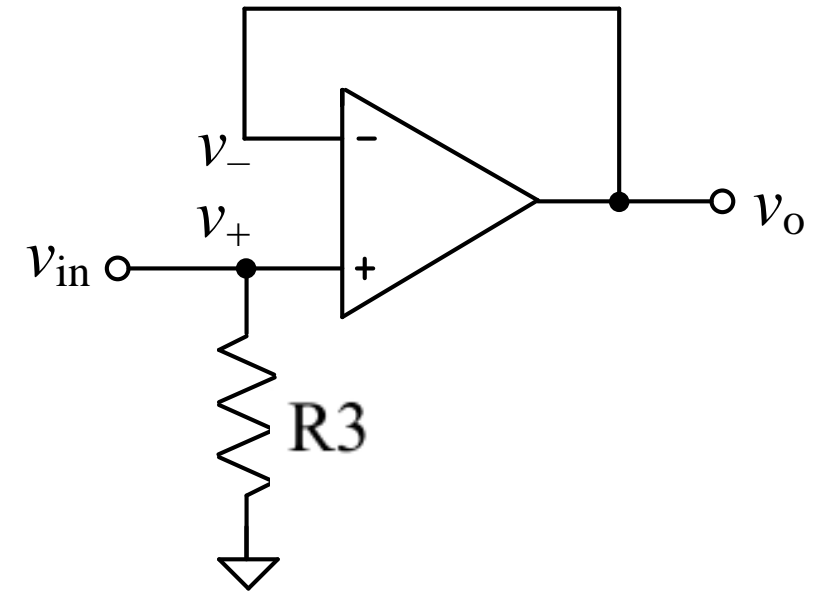
It is a special case of the non-inverting amplifier. with $R_1 \rightarrow \infty$ and $R_2 \rightarrow 0$.

Voltage gain: $A_v = 1 + R_2/R_1 \rightarrow 1$.

Input resistance: $R_{in} = R_3$.

- R3 is dropped in many applications. It provides unity voltage gain and large current gain.

- *Application:* Buffer amplifier with very high R_{in} and very low R_o . It is used for connecting a source with high source resistance to a relatively low-value load resistance without causing voltage attenuation.



5.4. Difference Amplifier

It combines inverting and non-inverting amplification for difference amplification.

Select $R_2/R_1 = R_4/R_3 = \alpha$.

Virtual short assumption: $i_1 = i_2$ & $i_3 = i_4$.

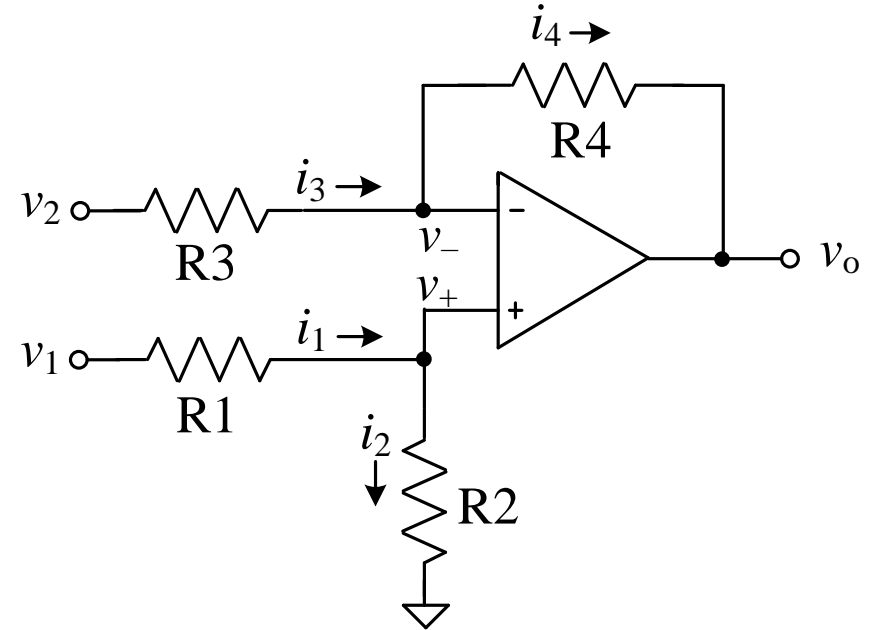
Use the superposition method. Find voltage gain & input resistance for each input by setting the other input as 0.

Circuit function: (i) attenuator & non-inverting amplifier for v_1 , (ii) inverting amplifier for v_2 .

$$\begin{aligned} v_o &= \left[\frac{R_2}{R_1 + R_2} v_1 \right] \left[1 + \frac{R_4}{R_3} \right] - \left[\frac{R_4}{R_3} v_2 \right] \\ &= \left[\frac{\alpha}{1 + \alpha} v_1 \right] [1 + \alpha] - [\alpha v_2] = \alpha(v_1 - v_2) \end{aligned}$$

- DM gain $A_d = \alpha$. CM gain $A_c = 0$. $R_{in1} = R_1 + R_2$, $R_{in2} = R_3$.
- Problems: (i) matched resistances needed, (ii) difficult gain control, (iii) unequal input resistances.
- A voltage v_3 (or DC bias) can be added to the output by connecting R2 to this voltage in place of ground.

$$v_o = \alpha(v_1 - v_2) + \left[\frac{1}{1 + \alpha} v_3 \right] [1 + \alpha] = \alpha(v_1 - v_2) + v_3$$



5.5. Summing & Difference Amplifier

Virtual short assumption

$$v_{i-} = v_{i+}, \quad i_1 + i_2 = 0, \quad i_3 + i_4 = i_5.$$

Use superposition method. Find voltage gain & input resistance for each input by setting other inputs as 0.

$$A_1 = [R_2 / (R_1 + R_2)] [1 + R_5 / (R_3 \parallel R_4)]$$

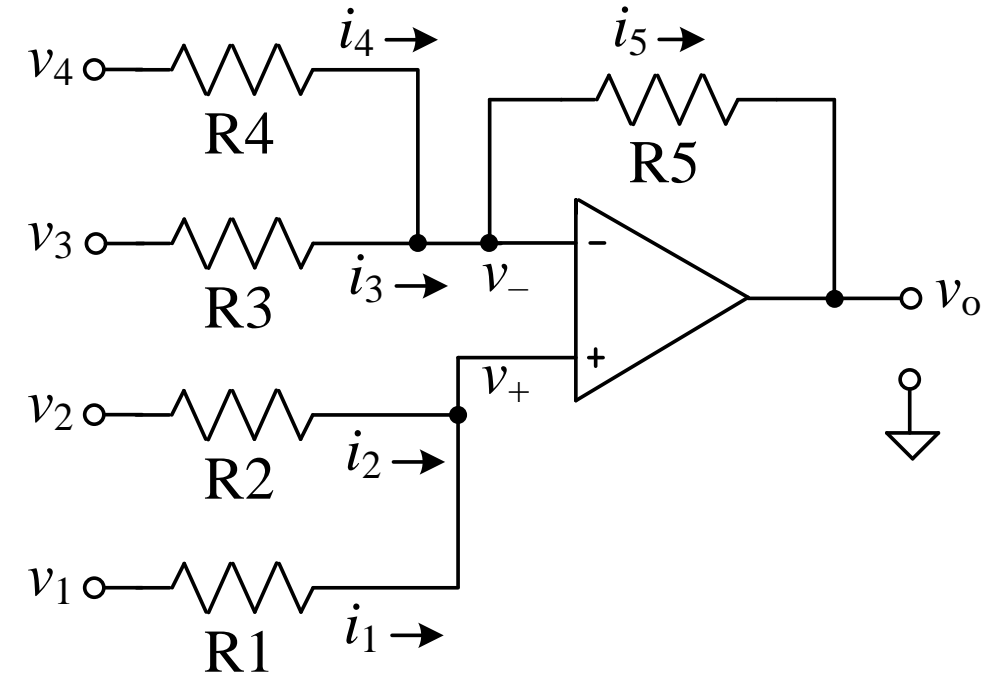
$$A_2 = [R_1 / (R_1 + R_2)] [1 + R_5 / (R_3 \parallel R_4)]$$

$$A_3 = -R_5 / R_3, \quad A_4 = -R_5 / R_4$$

$$R_{in1} = R_1 + R_2, \quad R_{in2} = R_1 + R_2,$$

$$R_{in3} = R_3, \quad R_{in4} = R_4.$$

- It has convenient inverting gain controls, independently by R_3 & R_4 , together by R_5 .
- Non-inverting gain controls are more difficult. The circuit can be extended for multiple inputs.

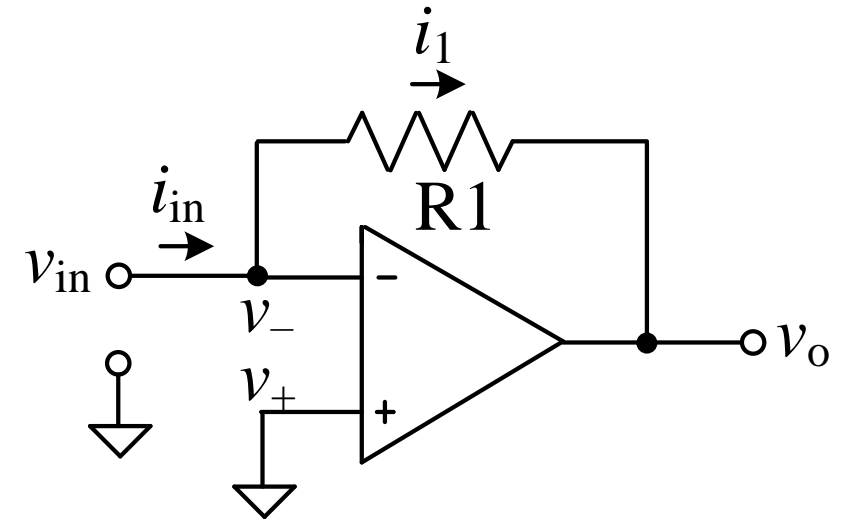


5.6. Current-to-Voltage (I/V) Converter (Trans-resistance Amplifier)

Virtual short assumption: $v_{i-} = v_{i+} = 0$. $i_1 = i_{in}$.

Therefore, $v_o = v_{i-} - R_1 i_{in} = -R_1 i_{in}$

$R_{in} = v_{in} / i_{in} = 0$.



Application: I/V converter for input current with ground as the return. For current not having ground return, another circuit with three op amps (not discussed here) is used.

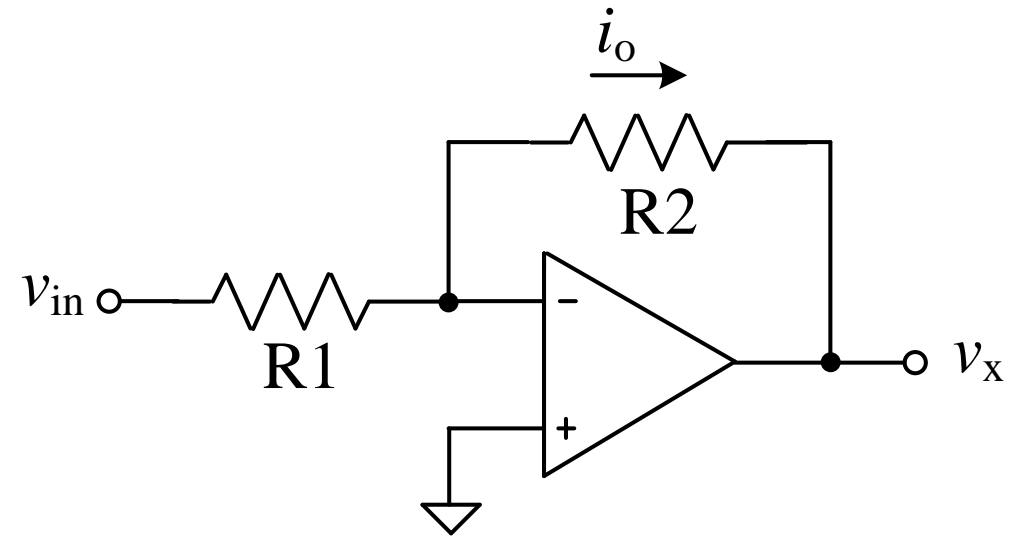
5.7. Voltage-to-Current (V/I) Converter (Trans-conductance Amplifier)

Re-purposed inverting amplifier circuit, for output current in load R2.

$$i_o = v_{in} / R_1$$

$$R_{in} = R_1$$

$$v_x = -R_2 i_o$$



- R_2 is limited by voltage swing at v_x .
- This circuit is for a floating load (load with no restriction on the connection of either terminal). Another circuit (not discussed here) is used for the grounded load (load with one terminal connected to the ground).
- Current from the input source is the same as load current i_o . To avoid loading the source, a buffer amplifier may be needed before the V/I converter.
- A V/I converter circuit can be used as an integrator by placing a capacitor in place of R_2 .

5.8. Polarity-Controlled Amplifier

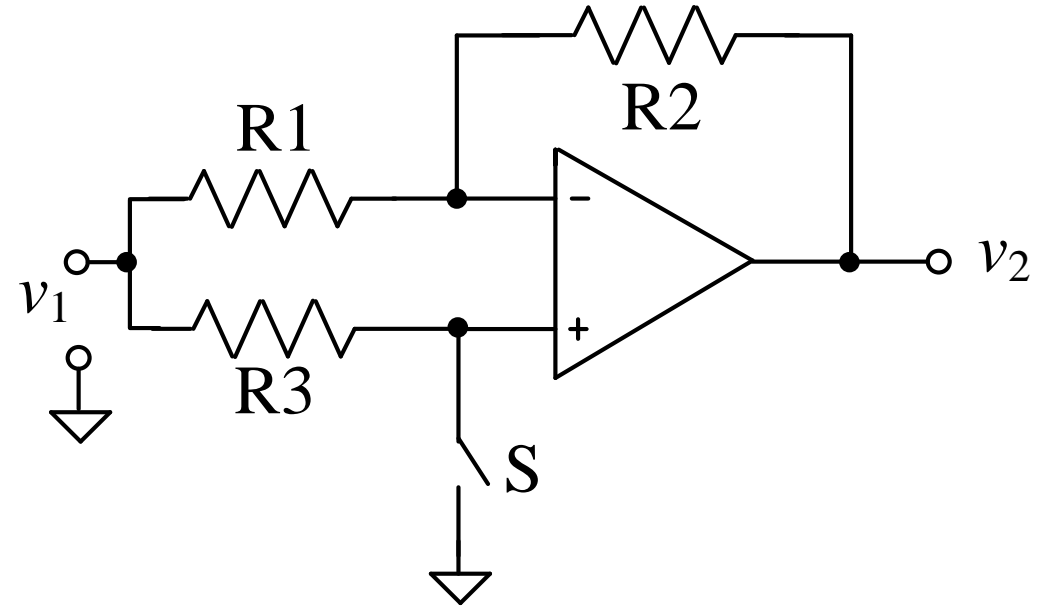
In this circuit, the voltage gain is changed between +1 and -1 using an electronically controlled switch.

S: electronically controlled switch.

Let $R_1 = R_2$

S closed: $v_2 = (-R_2/R_1) v_1 = -v_1 \Rightarrow A = -R_2/R_1 = -1$

S open: $v_2 = (-R_2/R_1) v_1 + (1+R_2/R_1) v_1 = v_1 \Rightarrow A = +1$



Thus, the circuit gain can be set as +1 or -1 using the electronically controlled switch S.

It is a simple example of 'programmable' or 'digitally-controlled' analog circuit.

5.9. AC Amplifiers

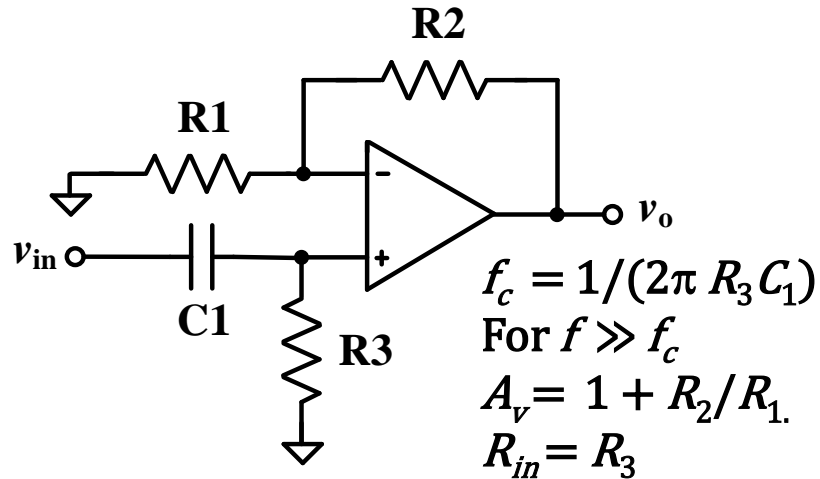
- The direct-coupled (DC) amplifiers (all circuits studied so far) have frequency-independent gain.
- For amplifying small time-varying AC components superimposed on a large constant (DC) component, a capacitor is connected in series with the input to block the DC component & couple the AC components. These amplifiers are known as alternate-coupled (AC) amplifiers. They have zero gain at zero frequency and nearly constant gain at high frequencies.
- Both inverting and non-inverting DC amplifiers can be changed to corresponding AC amplifiers. The capacitor value is selected such that its impedance at the lowest signal frequency (f_{min}) \ll input resistance R_{in} .
- We will study an AC inverting amplifier and an AC non-inverting AC amplifier, each using a single capacitor. These circuits are examples of "first order high-pass filters".
- A filter is a circuit with its gain varying with frequency. High-pass filters provide zero gain at DC and nearly constant gain at high frequencies. Other filters: low-pass, band-pass, band-stop, etc.
- All practical op amp inputs need a small current, known as input bias current. To permit this current flow, all op amp circuits must have a DC current path from each op-amp input terminal to Gnd.

AC Amplifier Examples

The inverting and non-inverting DC amplifiers are converted to the corresponding AC amplifiers by connecting a capacitor in series with the input. The capacitor value is selected such that its impedance at the lowest signal frequency $f_{min} \ll$ input resistance R_{in} .

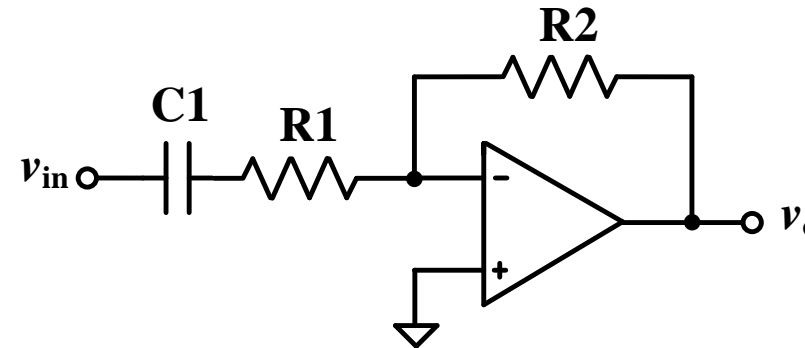
AC Non-inverting Amplifier

C_1 selection: $1/(2\pi f_{min} C_1) \ll R_3$



AC Inverting Amplifier

C_1 selection: $1/(2\pi f_{min} C_1) \ll R_1$



Practical op amp inputs need a small DC current, known as input bias current. To permit this current flow, there must be a DC current path from each op-amp input terminal to Gnd.

- Input bias current paths in the AC non-inverting amplifier: R_3 for the non-inverting input, R_1 and R_2 for the inverting input.
- AC inverting amplifier: direct connection to Gnd for the non-inverting input, R_2 for the inverting input.

6. Practical Op Amp

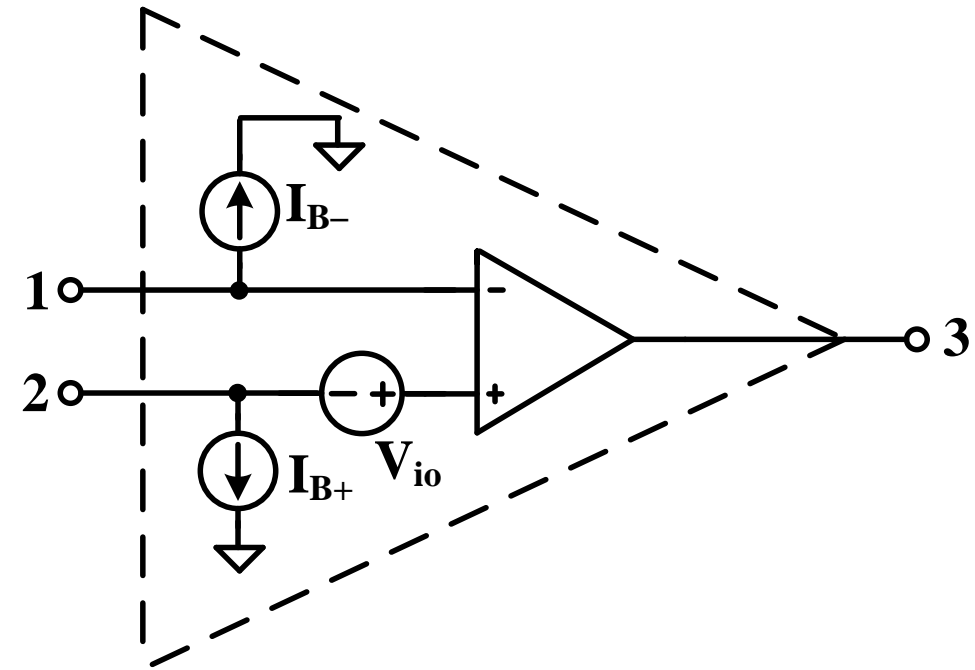
- For linear operation of an op amp, the CM input voltage, output voltage, and output current should be within the limits as set by the DC supplies & internal circuit of the op amp.

- DC imperfections:

- Input offset voltage (internal error voltage: 1–5 mV) causing output saturation in high-gain circuits.
- Input bias currents: Small DC input currents (10 pA to 100 nA). These must be permitted by external circuit for proper operation.

- Finite input & output resistances.

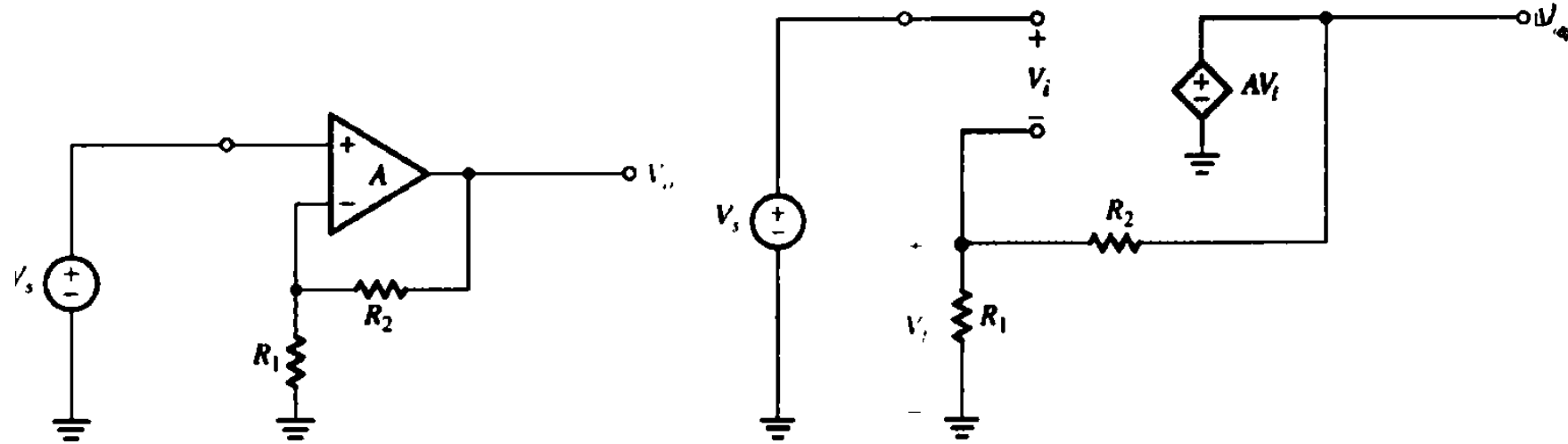
- Finite differential gain (typically $> 10^5$ at dc, decreasing with frequency), finite CMRR. Another limitation for large amplitude AC signals is “slew rate”, the maximum rate of change of output voltage (typically 1 V/ μ s).



Op-amp DC error model

7. Non-inverting Amplifier Analysis as a Negative Feedback Amplifier

- For a negative feedback amplifier with open-loop gain A & feedback factor $\beta \ll 1/A$, the closed-loop gain $A_f \approx 1/\beta$.
- In the non-inverting amplifier, the op-amp differential gain is the open-loop gain A .



β is set by the resistive attenuator (R_1, R_2), and it can be precise (very low variation as compared to A). Feedback is applied at the inverting input, and subtraction is using the op-amp differential input.

$$\beta = \frac{V_f}{V_o} = \frac{R_1}{R_1 + R_2} \Rightarrow A_f \approx 1/\beta = 1 + \frac{R_2}{R_1}, \text{ if } A \gg 1 + \frac{R_2}{R_1}$$

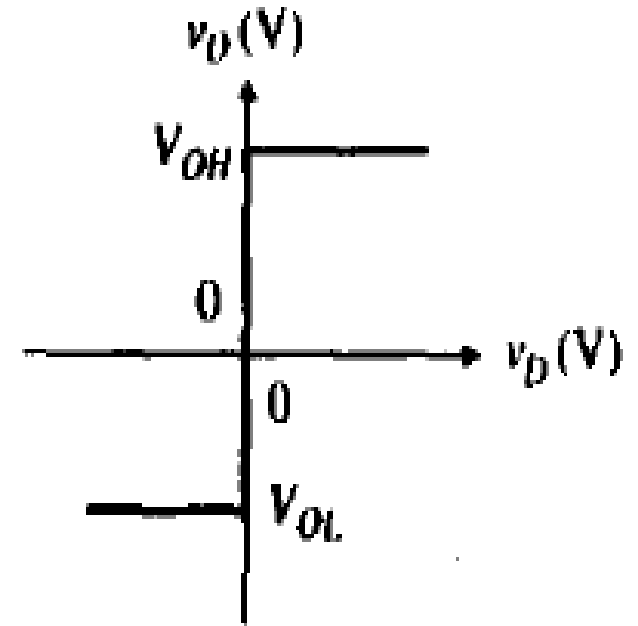
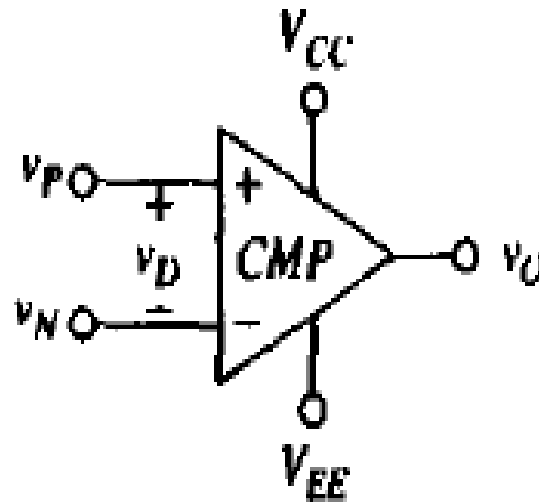
- A_f is precise if it is much smaller than A . Gain precision is at the expense of significant gain reduction. Other advantages (based on further analysis): very high R_{in} , very low R_o , increased bandwidth.
- All linear circuits analyzed using virtual short concept can be analyzed as negative feedback circuits.

8. Voltage Comparators

An op amp like device for open-loop operation & precise binary output levels.

$v_p > v_n$: $v_o = V_{OH}$ (high-level)

$v_p < v_n$: $v_o = V_{OL}$ (low-level)



- Circuit symbol: same as op amp symbol.
- Analog inputs & binary output. Input swing and output levels dependent on internal circuit and supply voltages (V_{CC+} , V_{EE-}).
- Transfer characteristic: very high gain at $v_d = 0$, i.e. about $v_p = v_n$, with sharp transition between the two output levels.
- A comparator is designed for very low input currents despite large differential input voltage. It has buffers at each input before the differential high-gain. An op amp can also be used as a comparator with due consideration for finite differential input voltage.
- Comparators & analog switches are the key components for interfacing the analog & digital circuits.

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