EE Dept, IIT Bombay
Academic Year: 2024-2025, Semester I (Autumn)

Course: MS101 Makerspace
EE Lectures: 04 & 05

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.

Instructors: PC Pandey, U Ganguly, SV Kulkarni, S Mondal, J John, D Saha, DK Sharma, KR Tuckley.

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.

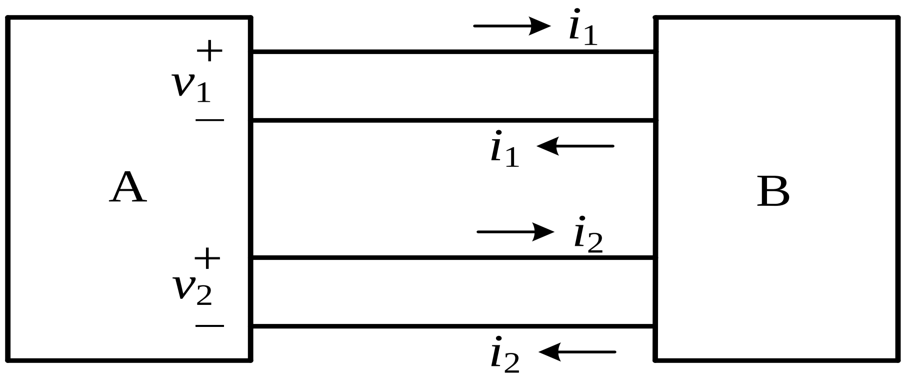
Distortion: A disturbance related to the signal.

Differential signals: Each signal needs two conductors.

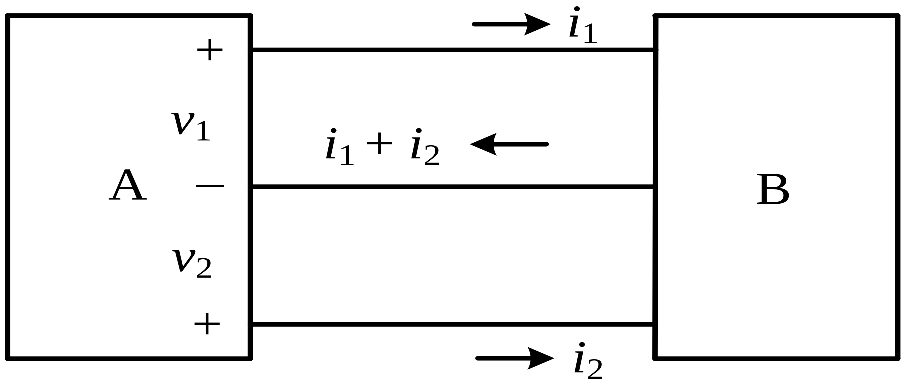
Single-ended signals: Several signals share a common reference in the case of voltage signals, & a common return in the case of current signals.

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.



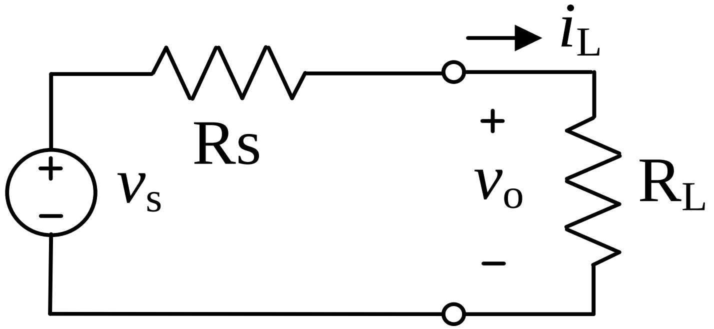
Two differential signals (each with two conductor)



Two single-ended signals (common reference & return)

Two signal representations

Voltage source model (Thevenin form)

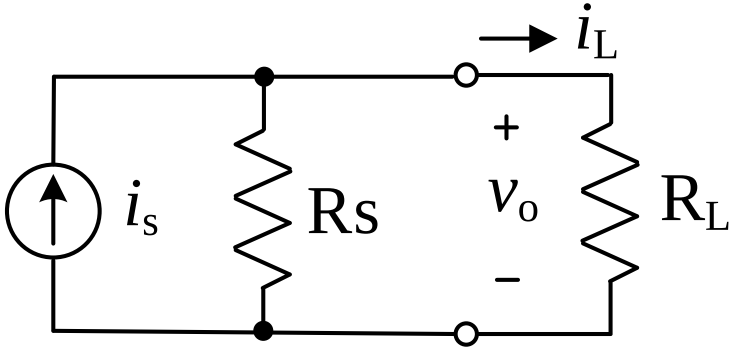


$$i_L = \frac{v_s}{R_s + R_L}$$

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

$$v_0 \approx v_s, \qquad R_L \gg R_s$$

Current source model (Norton form)



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

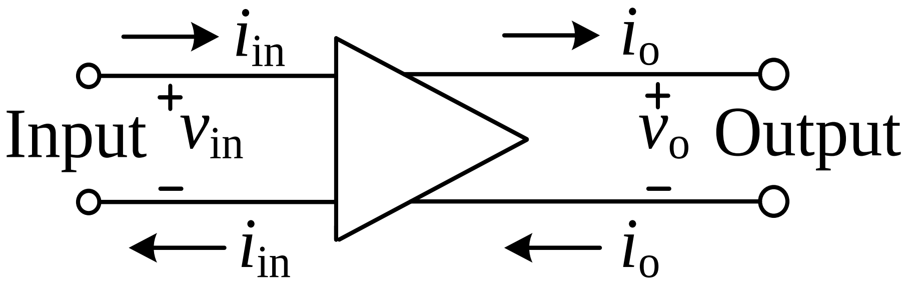
$$i_L = \frac{v_o}{R_L} = i_s \left(\frac{R_s}{R_s + R_L} \right)$$

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

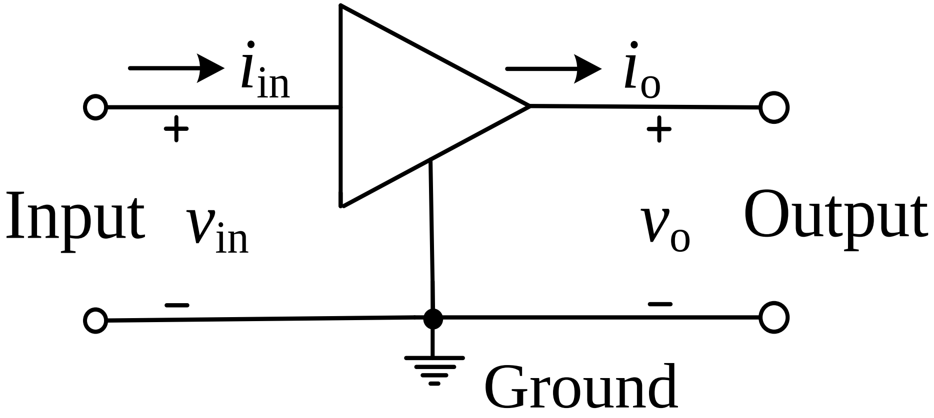
Preferred representation
Voltage source, if $R_s << R_L$. Current source, if $R_s >> R_L$.
Ideal voltage source: $R_s = 0$. Ideal current source: $R_s = \infty$.

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 diff. input & diff. output



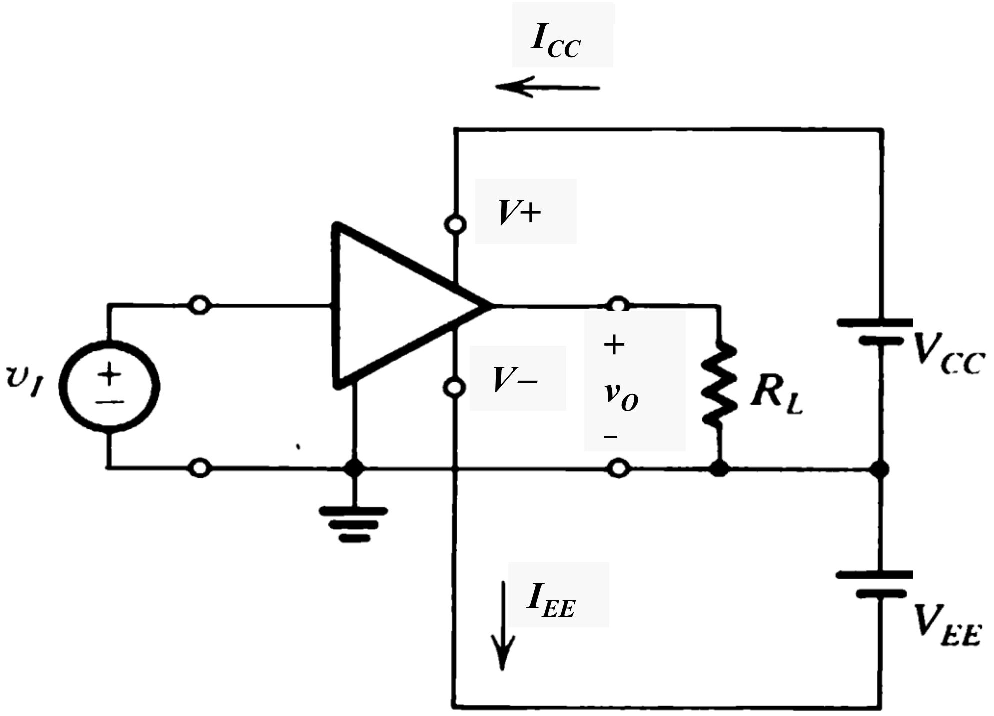
Amplifier with grounded input & grounded output

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

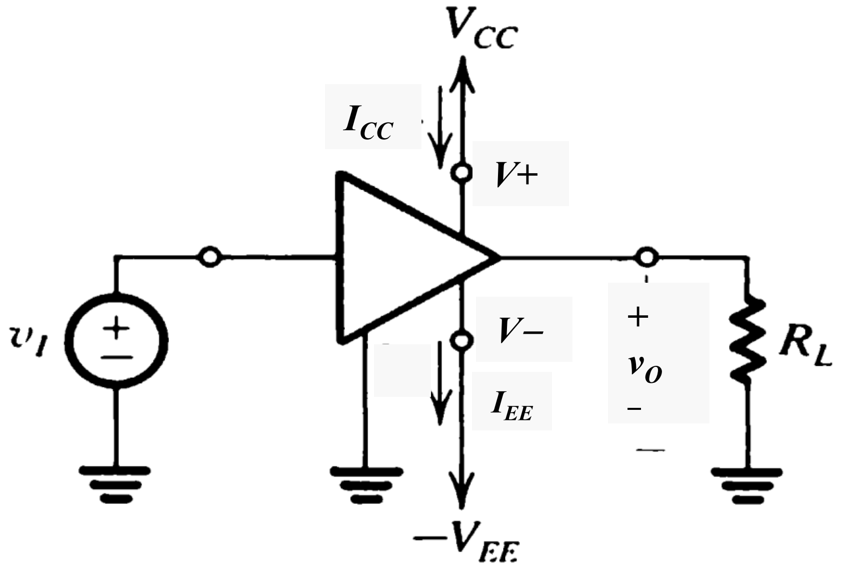
Amplifier power supplies

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.

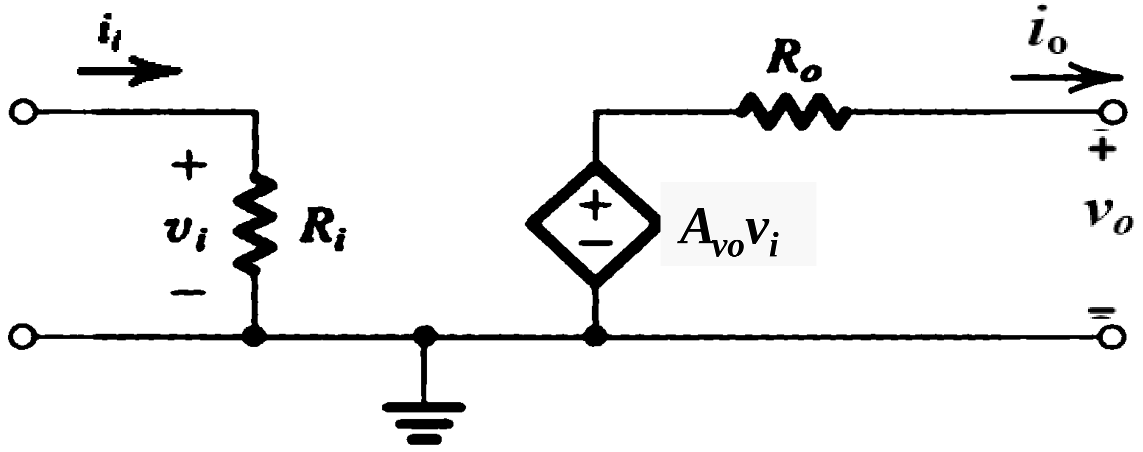


(b) Circuit diagram, with the circuit ground as the common reference for all voltages.

Single-ended amplifiers modeled as dependent sources

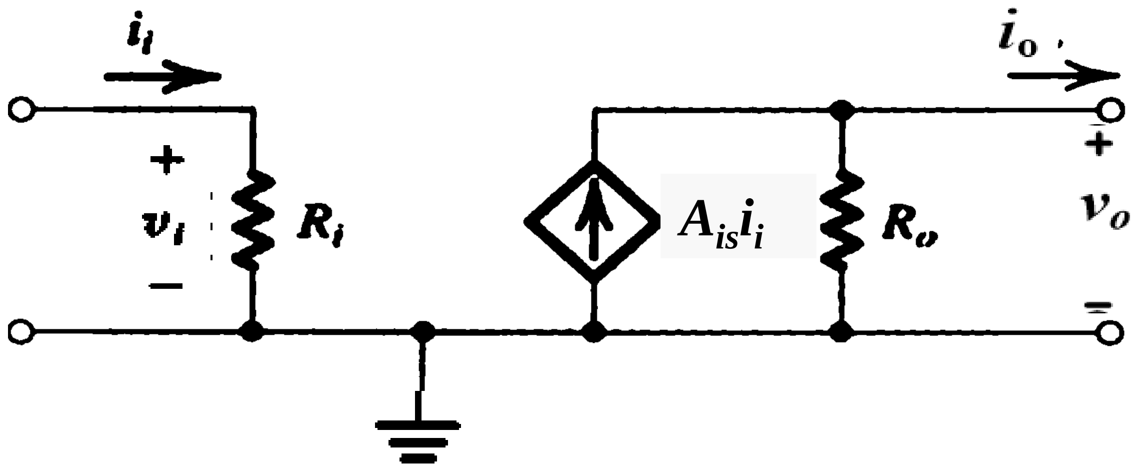
i) Voltage amplifier:

Voltage-controlled voltage source (VCVS)
Open-circuit voltage gain: A_{vo}
Ideal VCVS: $R_i = \infty$, $R_o = 0$



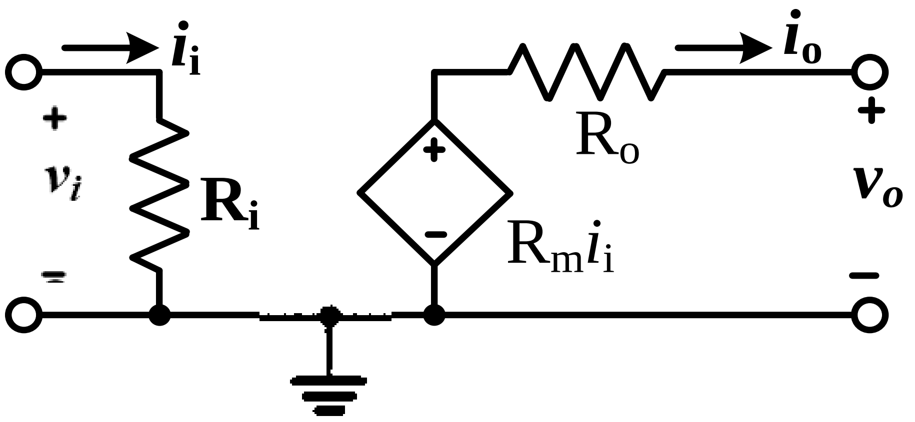
ii) Current amplifier:

Current-controlled current source (CCCS)
Short-circuit current gain: A_{is}
Ideal CCCS: $R_i = 0$, $R_o = \infty$



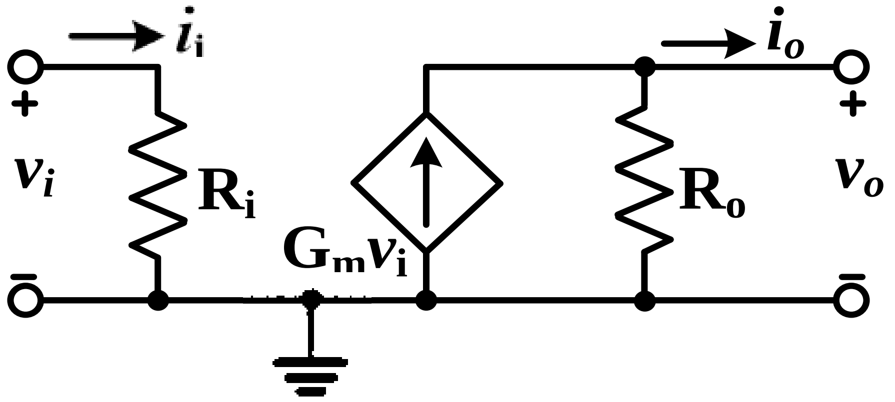
iii) Trans-resistance amplifier

Current-controlled voltage source (CCVS)
Open-circuit trans-resistance: R_m
Ideal CCVS: $R_i = 0$, $R_o = 0$



iv) Trans-conductance amplifier

Voltage-controlled current source (VCCS)
Short-circuit trans-conductance: G_m
Ideal VCCS: $R_i = \infty$, $R_o = \infty$



Differential signals

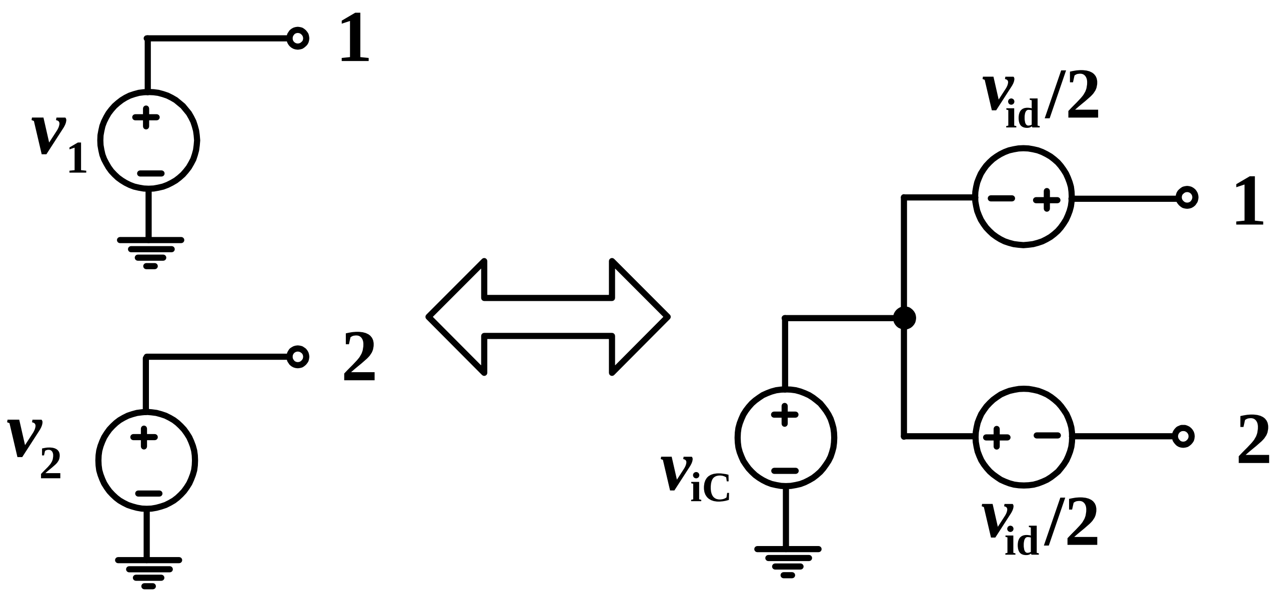
• A differential signal has two voltages with ground as the reference. The information is carried by the difference between the two voltages.

• 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.

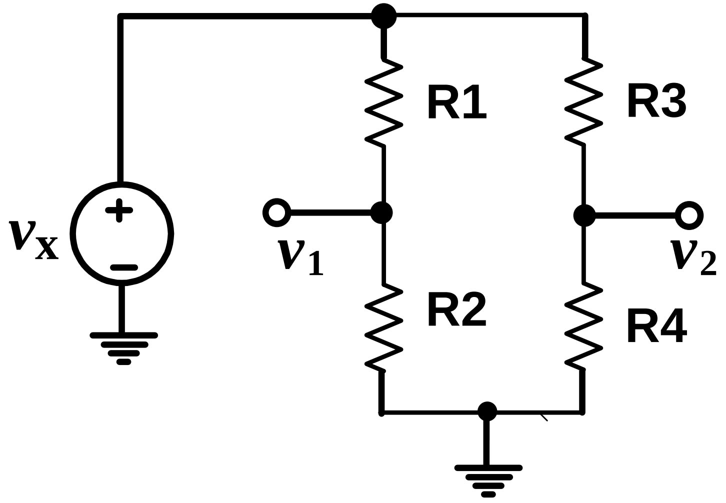
• Terminal voltages: v_1 & v_2

• 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 R1 and R2 is used to detect mismatch between R3 & R4. Excitation voltage: v_x . Output voltages: v_1 , v_2 .

$R_1 = R_2$. $v_1 = \frac{R_2}{R_1+R_2} v_x = \frac{v_x}{2}$. $v_2 = \frac{R_4}{R_3+R_4} v_x$

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

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

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

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

$$v_{ic} = \frac{v_1 + v_2}{2} = \frac{v_x}{2}\frac{1+\delta/4}{1+\delta/2} \approx (1-\frac{\delta}{4})\frac{v_x}{2}. \qquad v_{id} = v_1 - v_2 = \frac{v_x}{2}\frac{\delta/2}{1+\delta/2} \approx \frac{\delta}{4} v_x$$

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

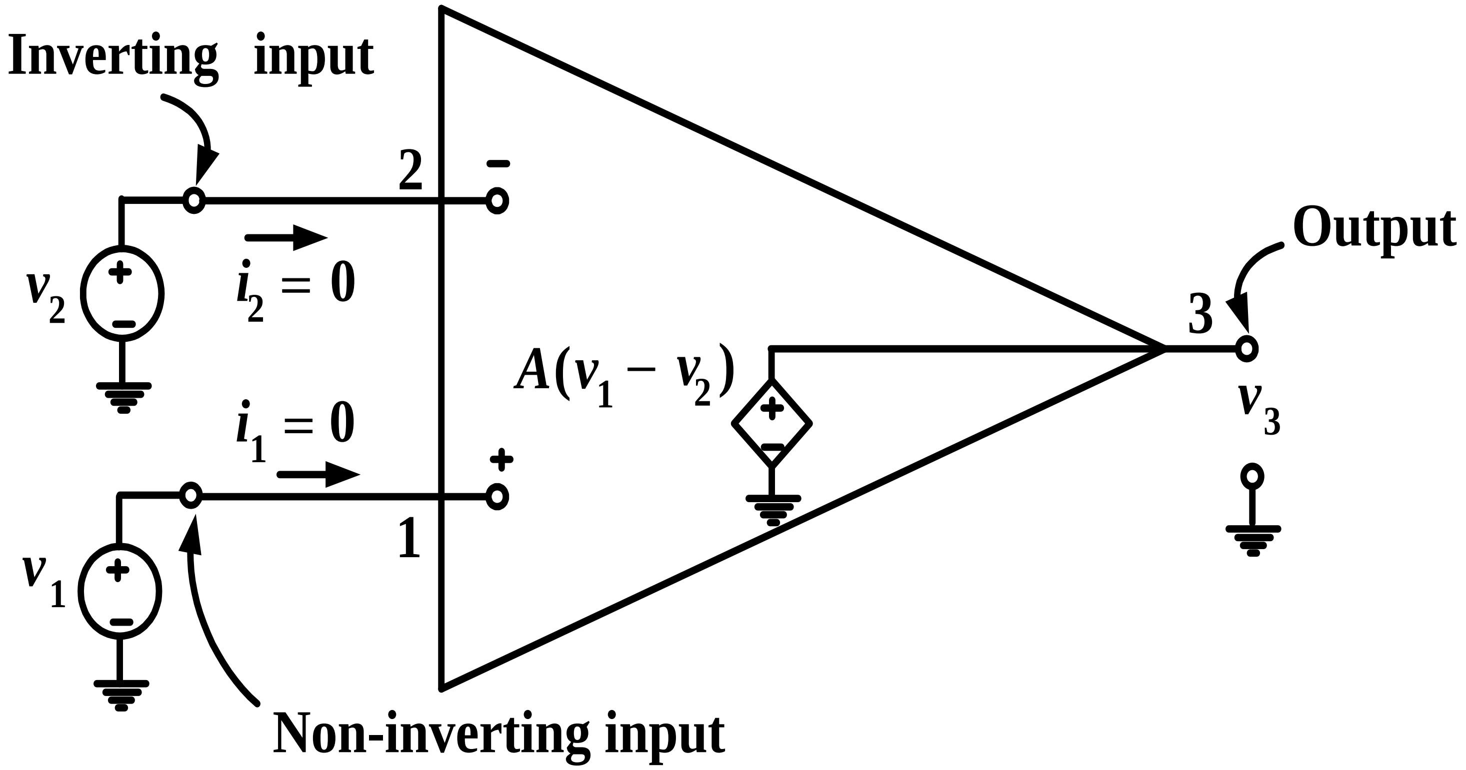
- Differential input voltage & single-ended output voltage
- Used to amplify the DM voltage while rejecting the CM voltage.

DM input voltage: $v_{id} = v_1 - v_2$
CM input voltage: $v_{ic} = (v_1 + v_2)/2$
$v_1 = v_{\mathrm{ic}} + v_{id}/2$; $v_2 = v_{\mathrm{ic}} - v_{id}/2$

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.

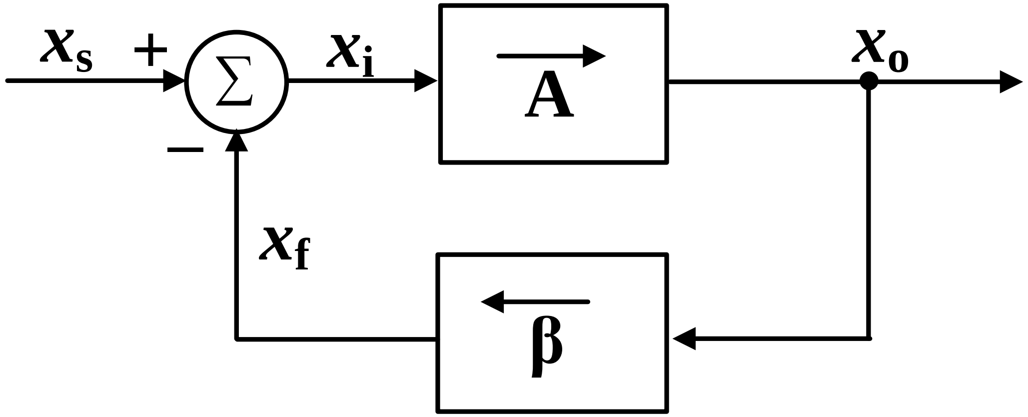
- **Negative feedback:** The output fraction opposes the input. It is used in amplifiers to
- desensitize the gain, making it less sensitive to the circuit component parameters;
- extend the bandwidth.;
- control the input and output resistances: raise or lower R_{in} and R_o by appropriate feedback 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).



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

- Feedback amplifier gain (closed-loop gain) $A_f = \dfrac{x_o}{x_s} = \dfrac{A}{1+A\beta}$. For $A\beta >> 1$, $A_f \approx \dfrac{1}{\beta}$.

•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 $A\beta >> 1$, 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

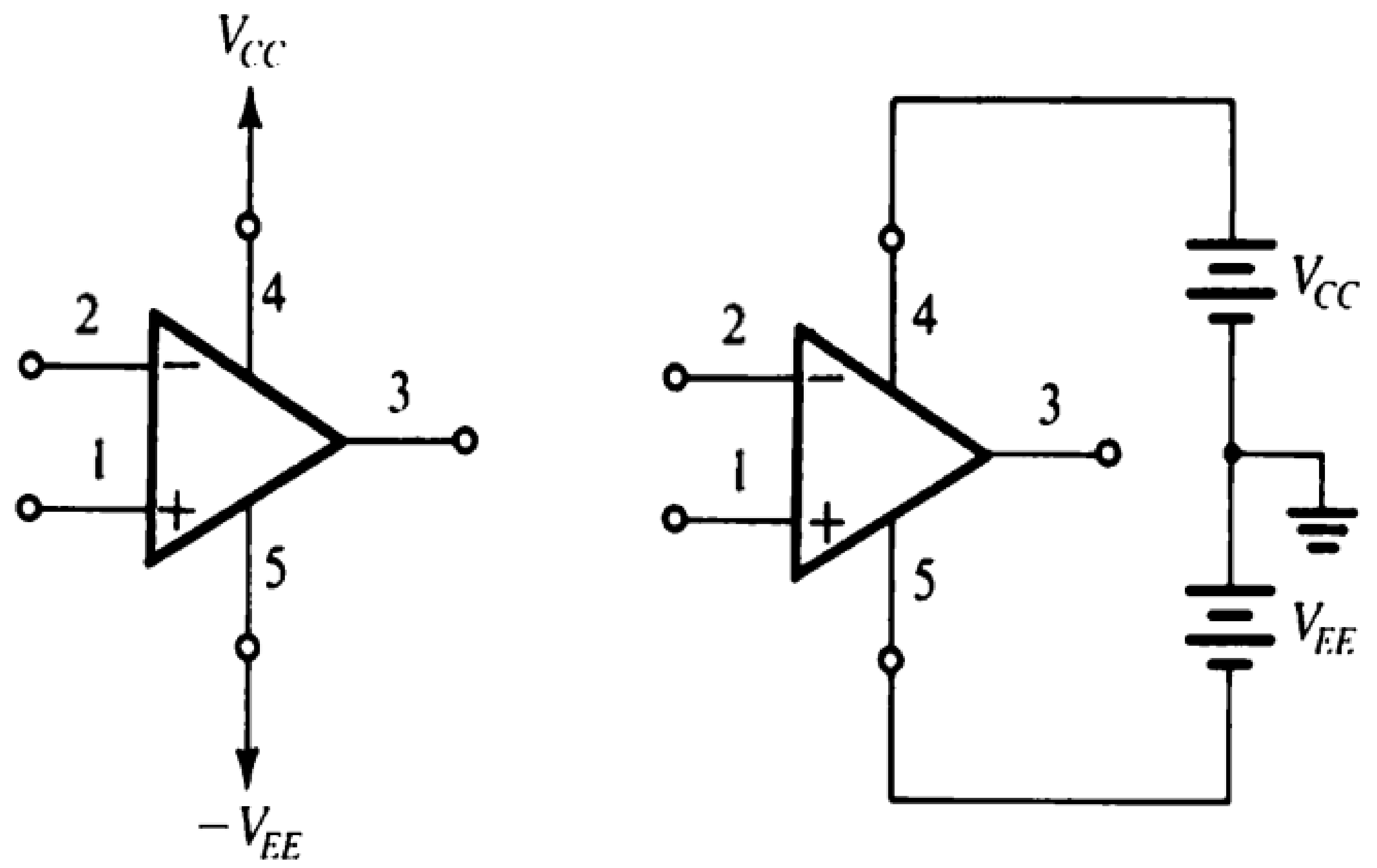
Operational amplifier (op amp, op-amp, or opamp)

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

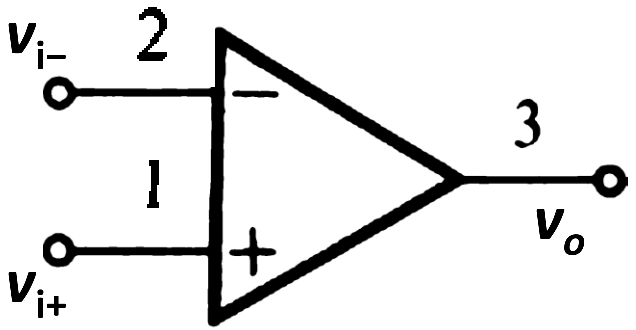
- Op amps were originally developed for mathematical operations on signal waveforms and are very convenient for designing circuits with feedback.
- Main objective: Circuit parameters should be determined by passive components & nearly independent of electronic device parameters.
- It is available as 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.

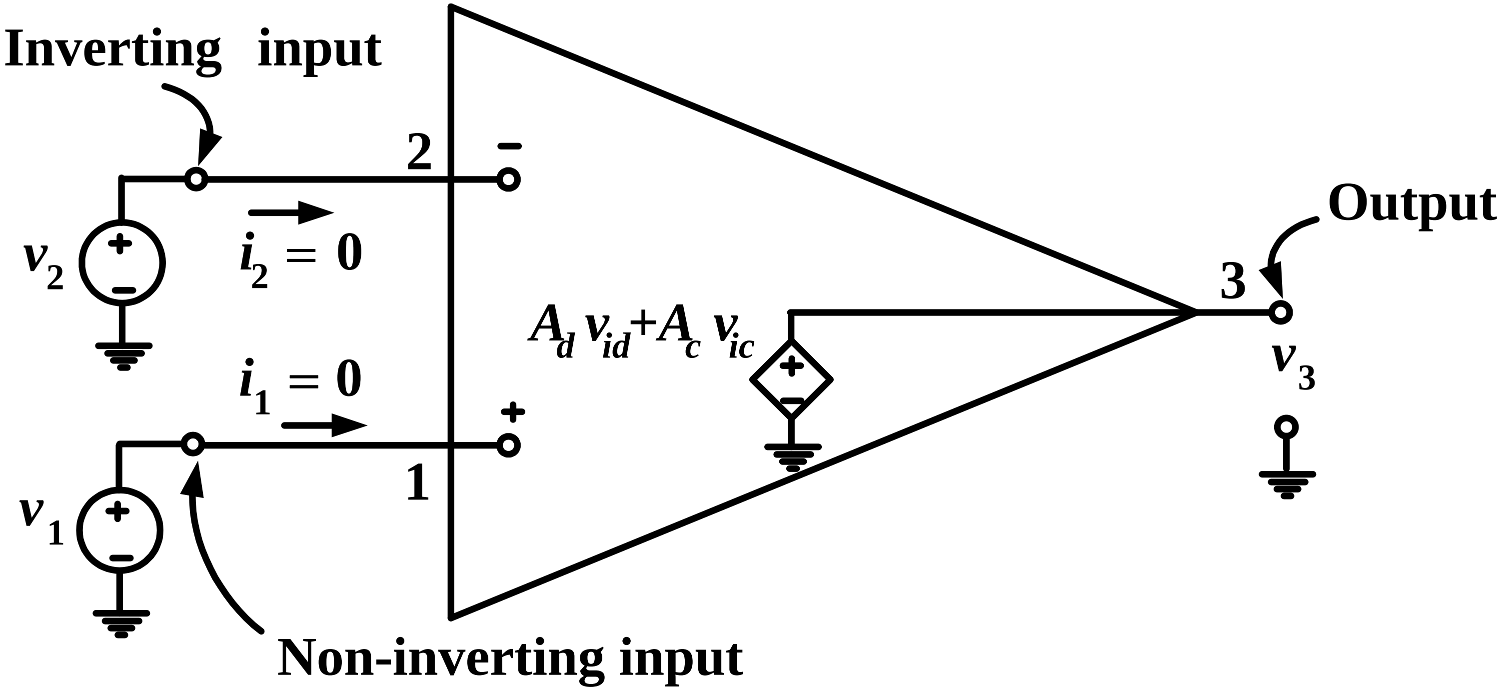
Input-output relation of an op amp

- 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:

CMRR $= A_d / A_c$.



Ideal op amp

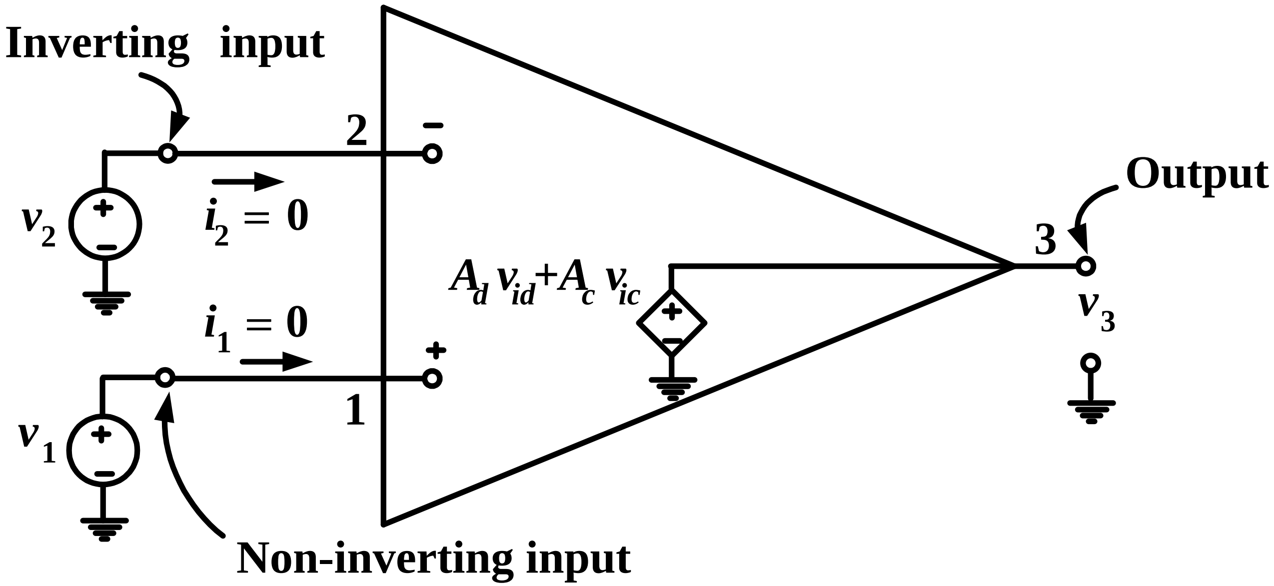
- $A_d \to \infty$. $A_c \to 0$. $v_3 = A_d(v_1 - v_2)$. CMRR $= A_d/A_c \to \infty$.
- DM input is amplified, with no effect of CM input on output. Required DM input $\to$ 0 for finite output.
- Infinite input resistance for both inputs: zero input currents.
- Zero output resistance: output voltage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

Linear operation of an op amp

• For an op amp operating in its linear region,

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

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, $A_d \to \infty$, $A_c \to 0$. Then for finite v_3, $v_{\text{id}} = v_3/A_d \to 0$.
Also, input resistances R_{i1}, $R_{i2} \to \infty$, so the input currents $\to 0$.

Thus, it appears as if the input terminals are shorted (since $v_{\text{id}} = 0$) 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

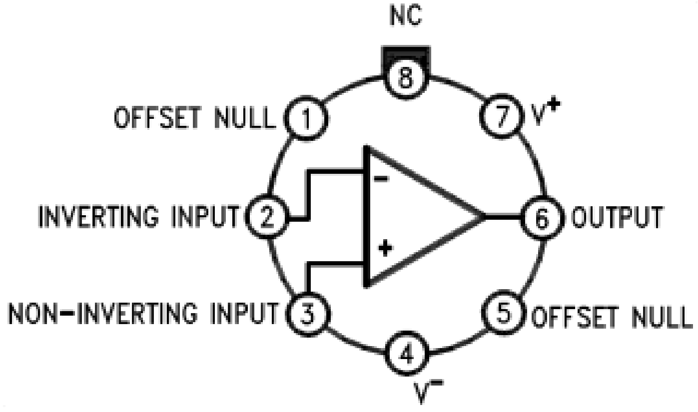
- Supply: ± 10 V to ± 18 V, ± 15 V typical.
- $A_d > 50 \times 10^3$.
- For ± 15 V supply,

Input range: ± 12 V.

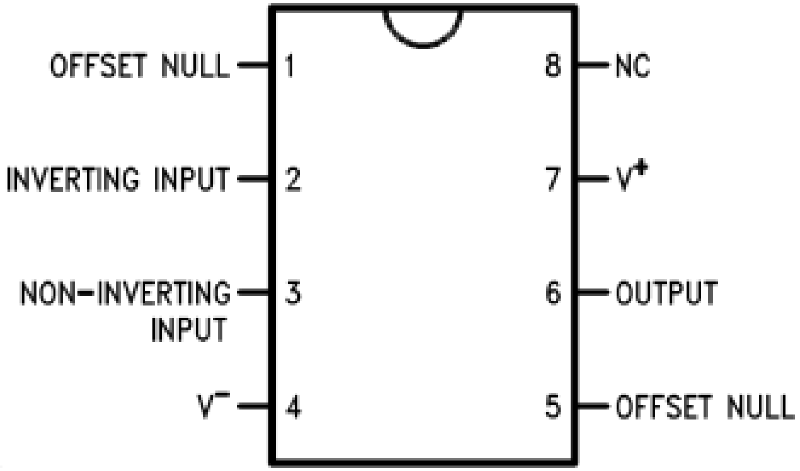
Output swing: ± 12 V.

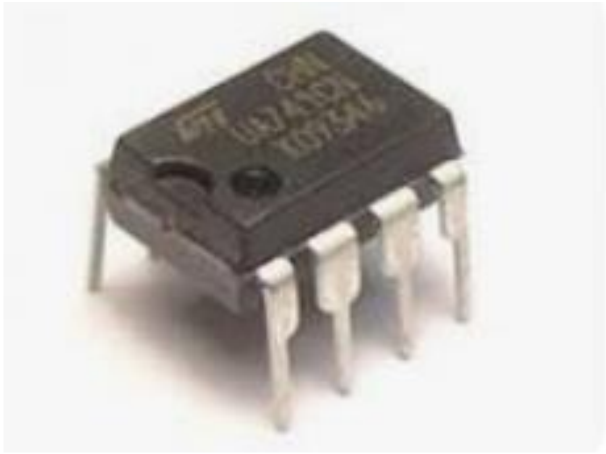
- Output short-circuit current: 25 mA.
- Power consumption < 100 mW.

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.

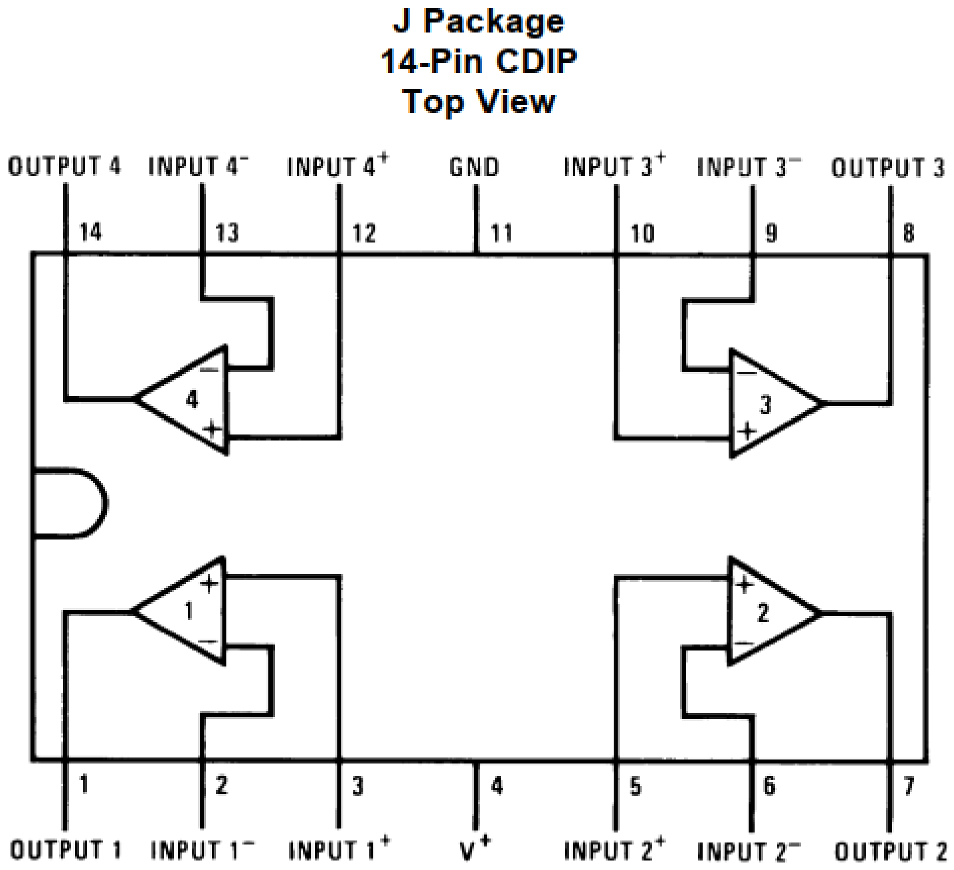
- Supply: $\pm$1.5 V to $\pm$16 V, $\pm$2.5 V typical.
- $A_d > 50\times10^3$.
- For 2.5 V & –2.5 V supply (dual supply operation),

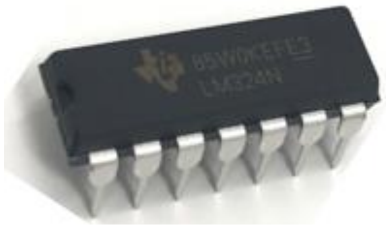
Input range: –2.5 V to 1 V. Output swing: –2.5 V to 1 V.

- 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 mW.

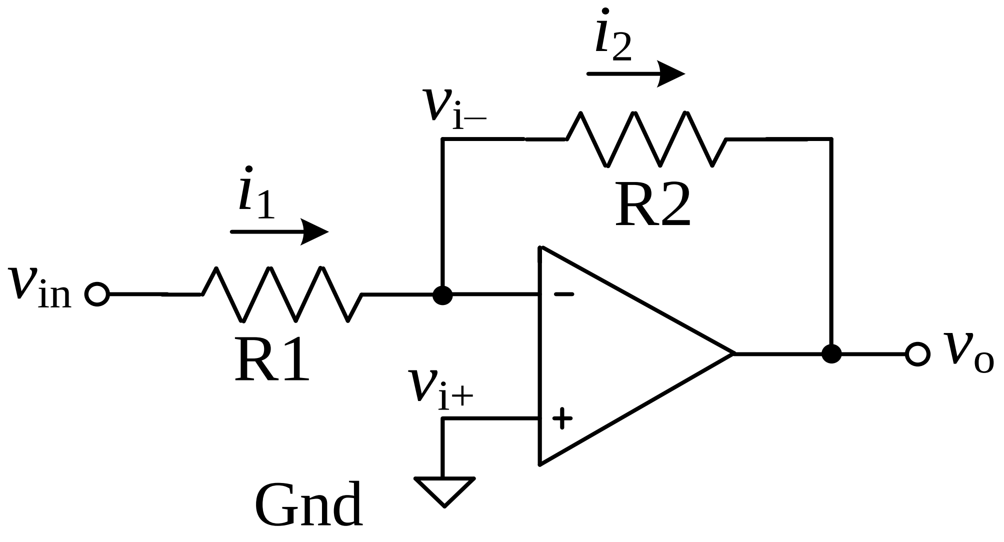




5. Linear Circuits

- 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: $R_{in} = v_{in} / i_1 = R_1$.
Output current for load R_L: $i_o = v_o/R_L$
Current gain: $A_i = i_o/i_1 = (v_o/R_L)/(v_{in}/R_1) = A_v(R_1/R_L)$.

- R_{in} can be decreased by connecting a resistor between the input and the ground.
- Current & power gains depend on the load resistance R_L between output and ground (not shown in the figure).
- The circuit operation is based on negative feedback. Check the virtual short assumption for disturbance in v_{i-}.

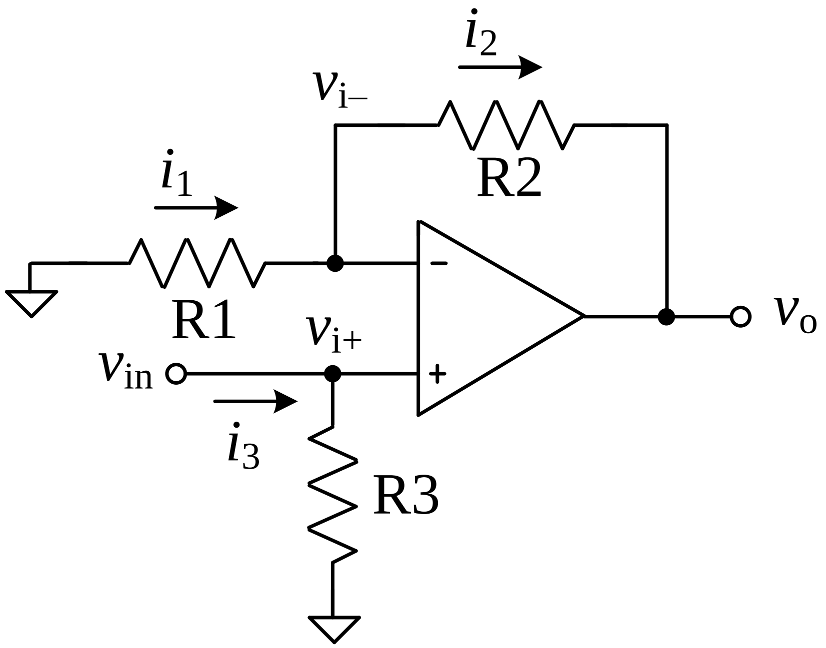
$v_{i-}\uparrow \;\rightarrow\; v_o\downarrow \;\rightarrow\; i_2\uparrow \;\rightarrow\; v_{i-}\downarrow \;\Rightarrow$ virtual short is restored. Same with $v_{i-}\downarrow$.

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: $R_1 = 10$ kΩ, $R_2 = 100$ kΩ. $R_L = 1$ kΩ. $A_v = -10$, $A_i = -100$, $A_p = A_v A_i = 1000$, $R_{in} = 10$ kΩ .

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 R_L between output and ground (not shown in the figure).

• Current gain: $A_i = i_o\,/i_3 = (v_o/R_L)\,/(v_{in}/R_3) = A_v(R_3\,/R_L)$.

• 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 $v_{i-}\downarrow$.

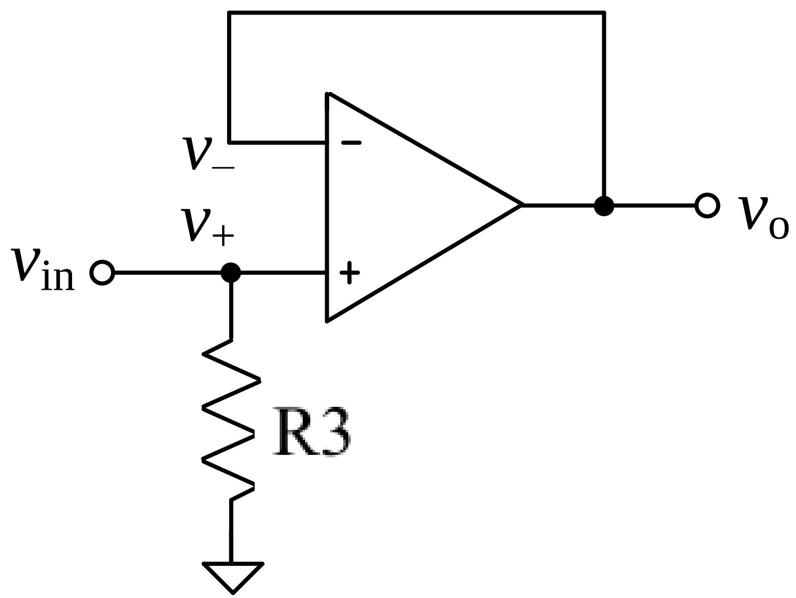
It can be seen that the virtual short is violated if the input terminals are interchanged.

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: $R_1 = 10$ kΩ, $R_2 = 100$ kΩ, $R_3 = 1$ MΩ, $R_L = 1$ kΩ. $A_v = 11$, $A_i = 1.1\times10^4$, $A_p = A_v A_i = 1.21\times10^5$, $R_{in} = 1$ MΩ .

5.3. Non-inverting Unity Follower (Unity Buffer)



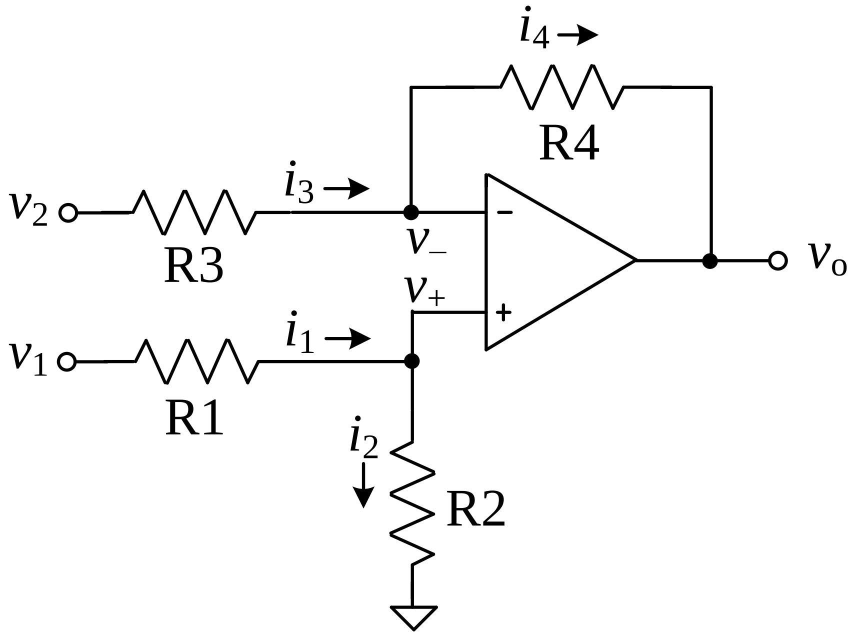
It is a special case of the non-inverting amplifier. with $R_1 \to \infty$ and $R_2 \to 0$.

Voltage gain: $A_v = 1 + R_2/R_1 \to 1$.
Input resistance: $R_{in} = R_3$.
Current gain: $A_i = (v_o/R_L)/(v_{in}/R_3) = R_3/R_L$.

R3 may be open circuit in many applications.

• *Application:* It provides unity voltage gain and large current gain. 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 superposition method. Find voltage gain & input resistance for each input by setting other input as 0.

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

$$v_o = \left[\frac{R_2}{R_1 + R_2} v_1\right]\left[1 + \frac{R_4}{R_3}\right] - \left[\frac{R_4}{R_3} v_2\right]$$

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

- 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

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

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

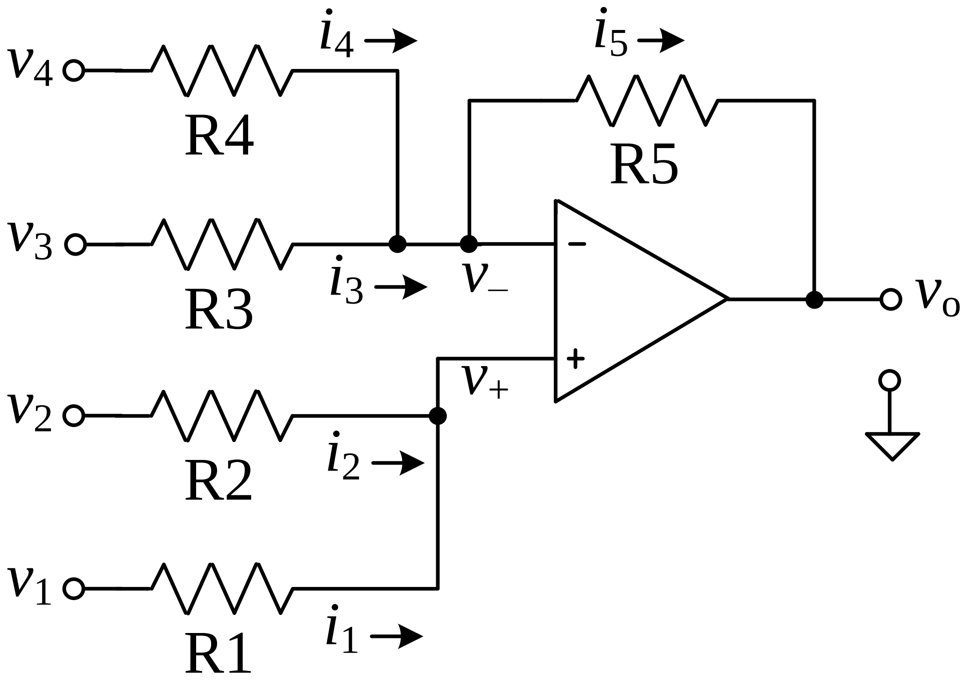
$A_1 = [R_2/(R_1+R_2)]\,[1+ R_5/(R_3 \| R_4)]$

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

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

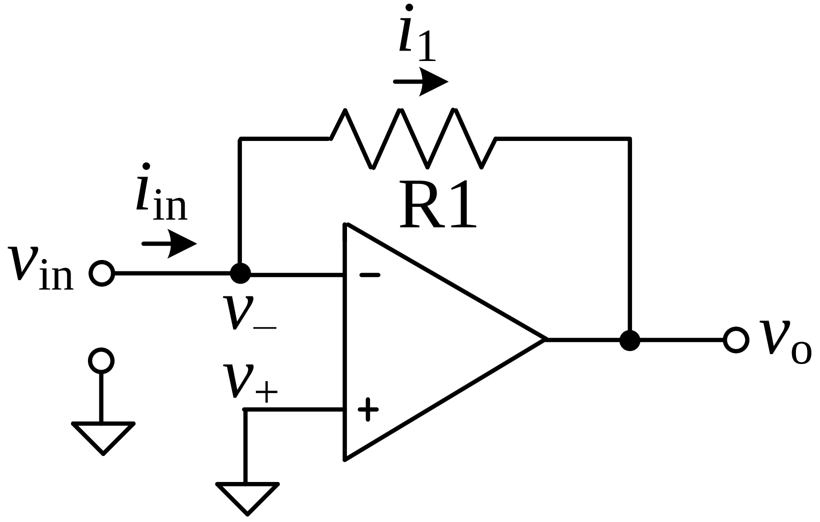
$R_{in1} = R_1 + R_2$, $R_{in2} = R_1 + R_2$,

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



- 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)



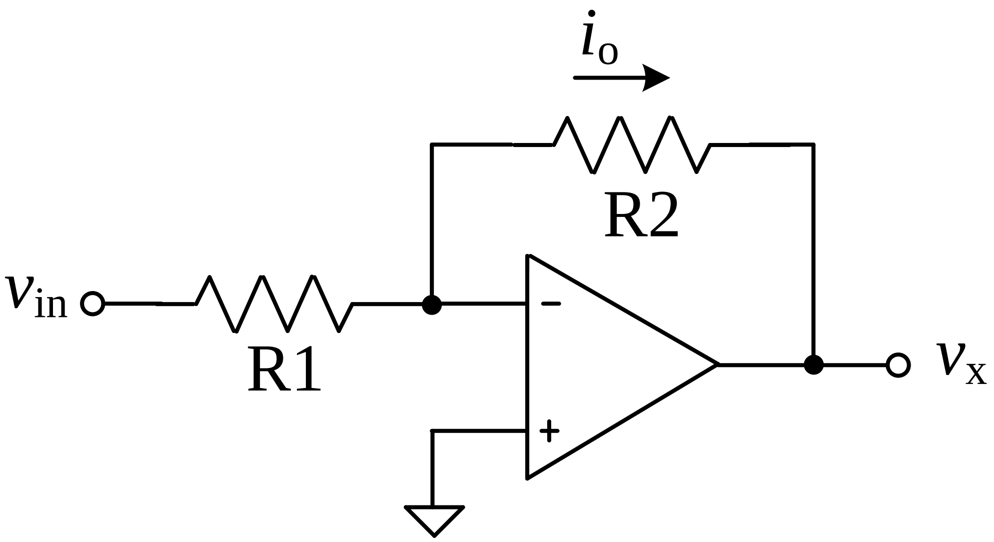
Virtual short assumption: $v_{i-} = v_{i+} = 0$. $i_1 = i_{in}$.

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 connection of either terminal). Another circuit (not discussed here) is used for grounded load (load with one terminal connected to 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 V/I converter.**
- **A V/I converter circuit can be used as an integrator by placing a capacitor in place of R2.**

5.8. Polarity-Controlled Amplifier

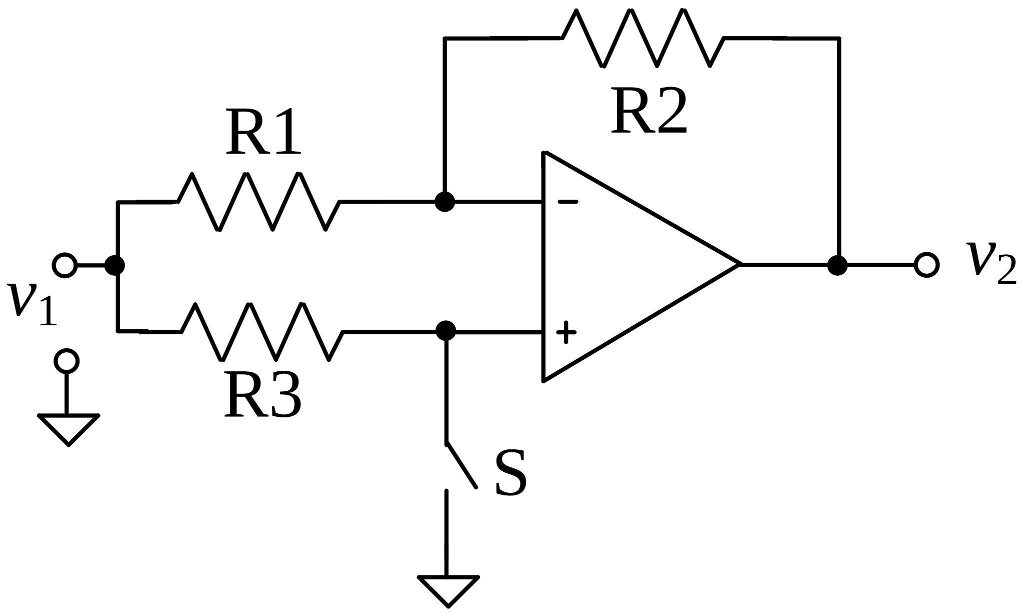
In this circuit, the voltage gain is changed between +1 and −1 using an electronically controlled switch.

S: electronically controlled switch.

Let $R_1 = R_2$

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

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.

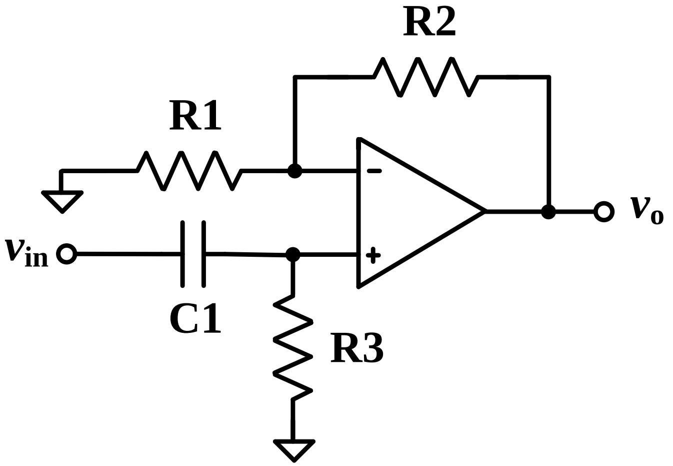
It is a simple example of 'programmable' or 'digitally-controlled' analog circuit.

5.9. AC Amplifiers

- The amplifiers studied so far have frequency-independent gain and are direct-coupled (DC) amplifiers.
- 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. This AC amplifier is a simple example of high-pass filters.
- 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 frequency (f_{min}) $<<$ input resistance R_{in} .

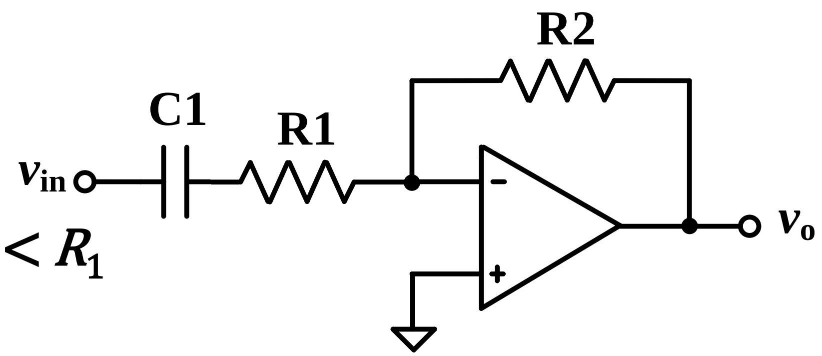
Non-inverting AC Amplifier

$1/(2\pi f_{min} C_1) << R_3$
$A_v = 1 + R_2/R_1$
$R_{in} = R_3$



Inverting AC Amplifier

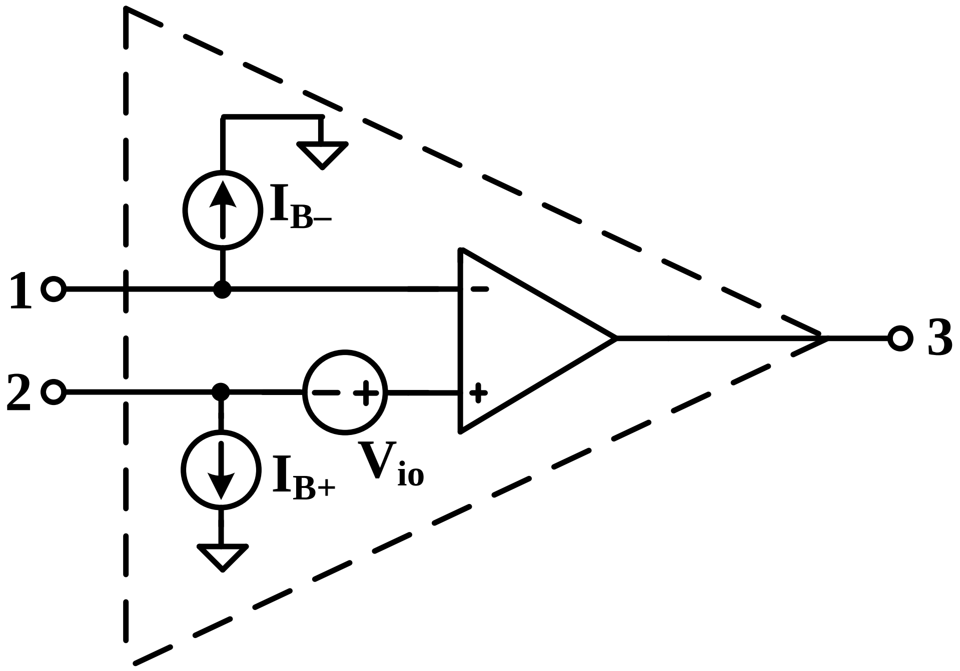
$1/(2\pi f_{min} C_1) << R_1$
$A_v = -R_2/R_1$
$R_{in} = R_3$



- 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. R3 is needed in the non-inverting AC amplifier to provide this path for the non-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.



Op-amp DC error model

- DC imperfections:

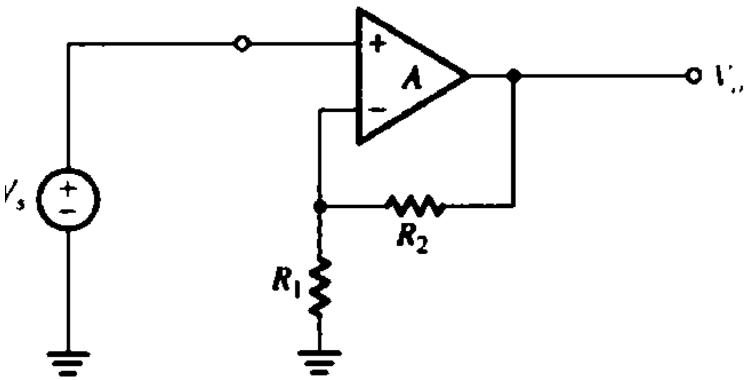
- Input offset voltage (internal error voltage: 1—5 mV) causing output saturation in high-gain circuits.
- Input bias currents: Small DC input currents (10 pA to 100 nA). These must be permitted by external circuit for proper operation.

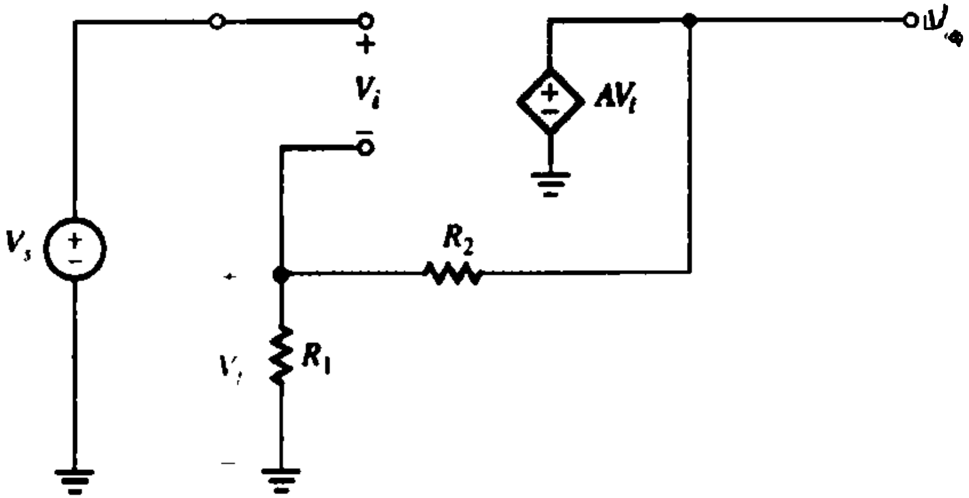
- Finite input & output resistances.
- Finite differential gain (typically > 10^5 at dc, decreasing with frequency), finite CMRR. Another limitation for large amplitude AC signals is “slew rate”, the maximum rate of change of output voltage (typically 1 V/μs).

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

• For a negative feedback amplifier with open-loop gain A & feedback factor β << $1/A$, 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 (R1, R2), 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.

$$\beta = \frac{V_f}{V_o} = \frac{R_1}{R_1 + R_2} \Rightarrow A_f \approx 1/\beta = 1 + \frac{R2}{R_1}, \text{ if } A >> 1 + \frac{R2}{R_1}$$

• 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.

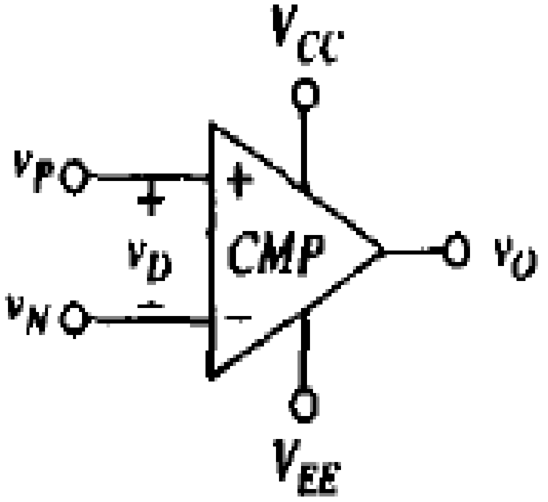
• All linear circuits analyzed using virtual short concept can be analyzed as negative feedback circuits.

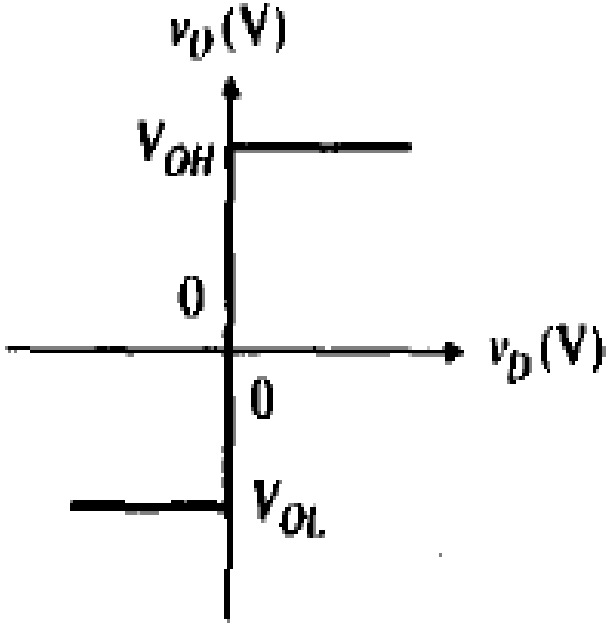
8. Voltage Comparators

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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