EE Dept, IIT Bombay
Academic Year: 2025-2026, Semester I (Autumn)

Course: MS101 Makerspace

EE Lectures 3 & 4

Operational Amplifier Circuits

Topics: (1) Signal Basics; (2) Amplifier; (3) Feedback Amplifier; (4) Op Amp; (5) Linear Circuits; (6) Practical Op Amp; (7) Non-inverting Amplifier as a Feedback Amplifier; (8) Voltage Comparator.

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).

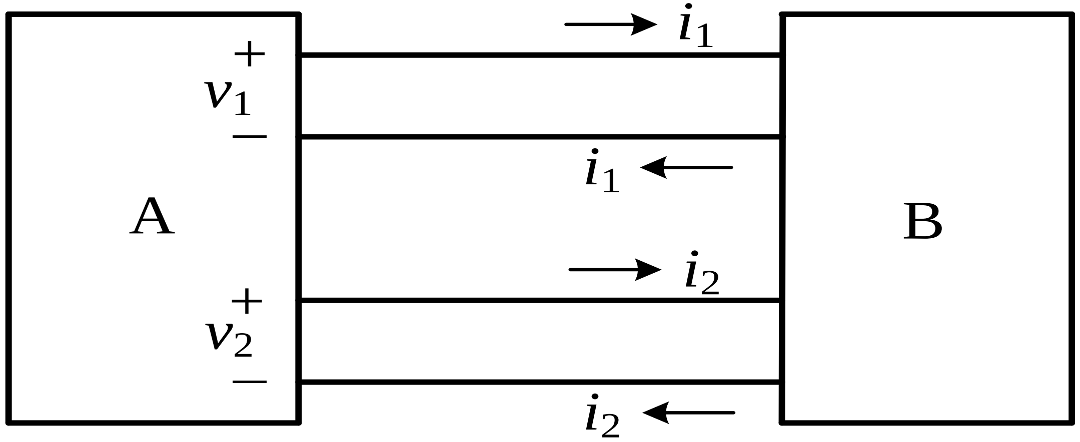
Noise: A disturbance unrelated to the signal.

Distortion: A disturbance related to the signal.

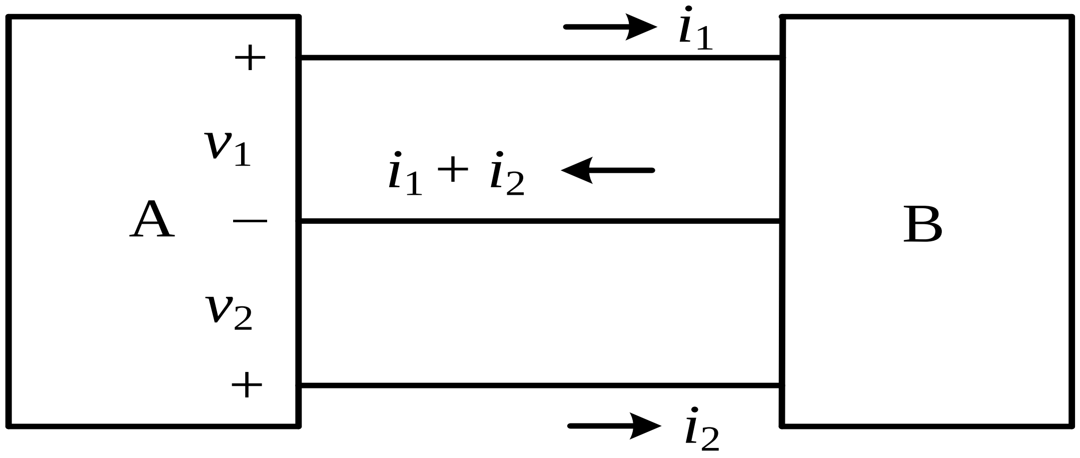
Differential signals: Each signal needs two conductors.

Single-ended signals: Several signals share a common reference for voltages & return for currents.

Two differential signals, each with two conductors.



Two single-ended signals, with common reference & return.

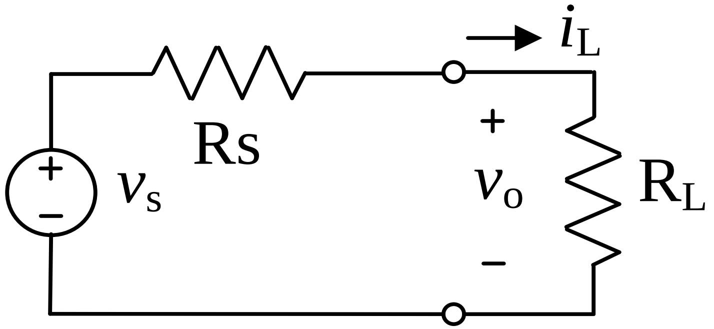


Circuit ground: A conductor or terminal (usually attached to a power supply terminal) serving as the common reference for voltages and return for currents.

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 Signal Representations

Voltage source model (Thevenin form)

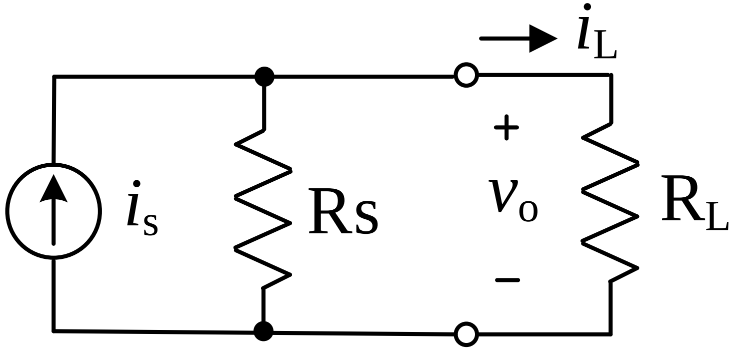


$$i_L = \frac{v_s}{R_s + R_L}$$

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

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

Current source model (Norton form)



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

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

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

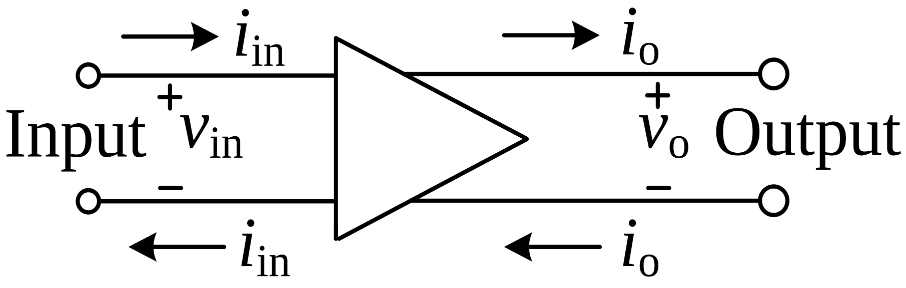
Preferred representation

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

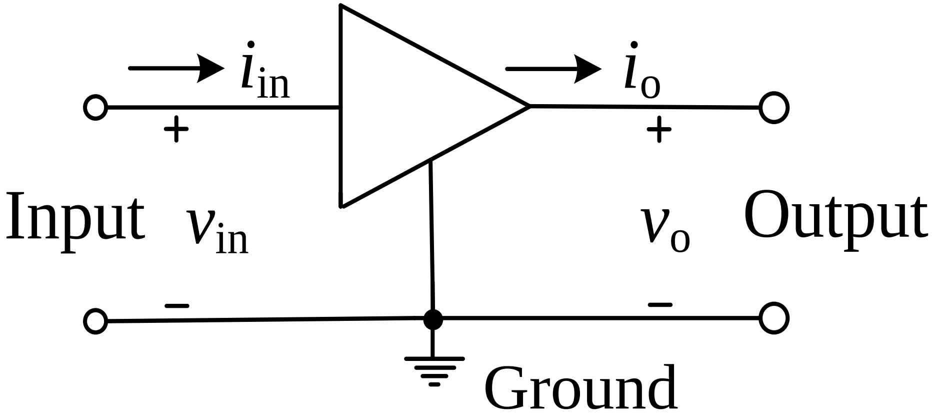
Ideal voltage source: $R_s = 0$. Ideal current source: $R_s = \infty$.

2. Amplifier

An amplifier is 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



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.**

2.1 Amplifier Power Supplies

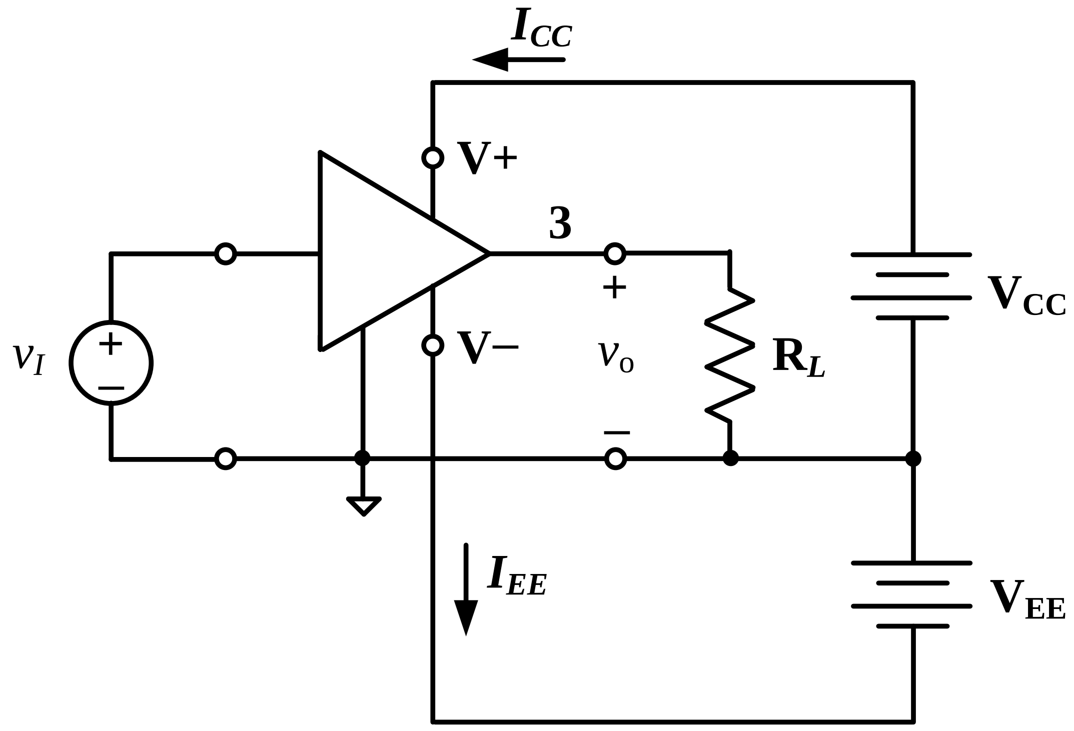
• An amplifier delivers more power to the output load than it draws from the input source. It needs dc power sources for the extra power delivered to the load as well as any power dissipated in the internal circuit.

• Dual supply amplifier: Two DC supplies, with the −ve terminal of one supply and the +ve terminal of the other supply connected to the circuit ground. Supply voltages need not be equal.

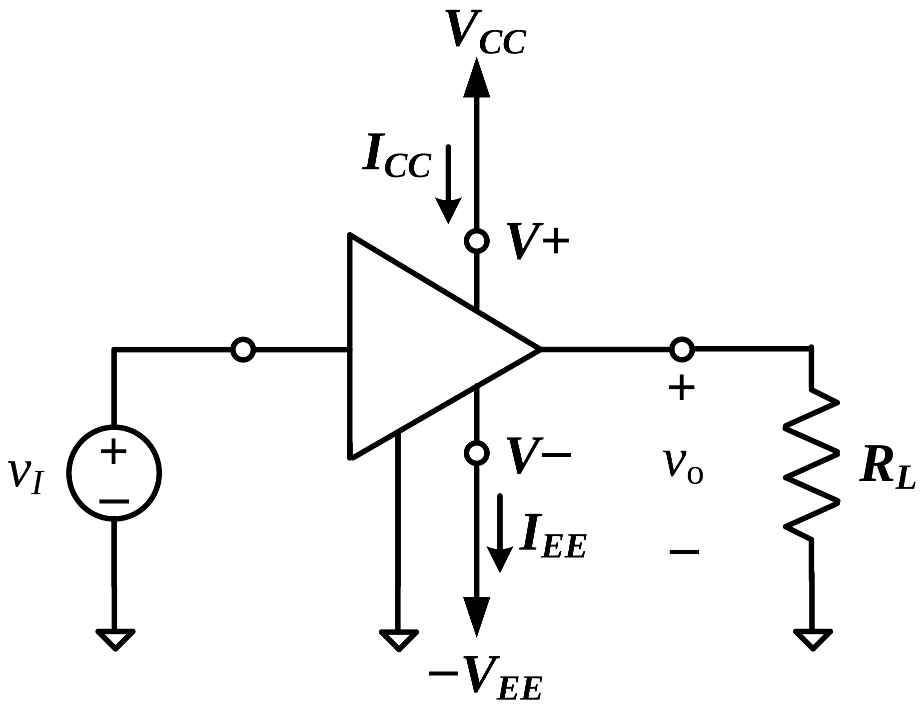
• Single supply amplifier: One of the two supply terminals of the amplifier is connected to the circuit ground, i.e. a dual supply amplifier with one of the supply voltages as zero.

• Input & output voltage swings are limited by the circuit & supply voltages.

(a) Circuit diagram with explicit supply connections.



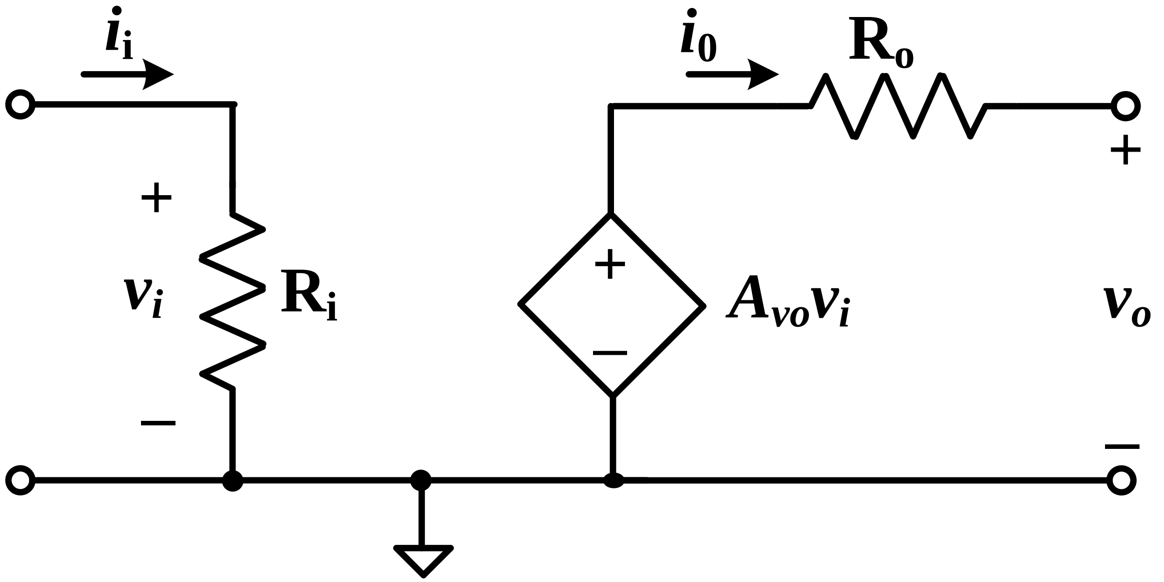
(b) Circuit diagram with implicit supply connections, with the circuit ground as the common reference.



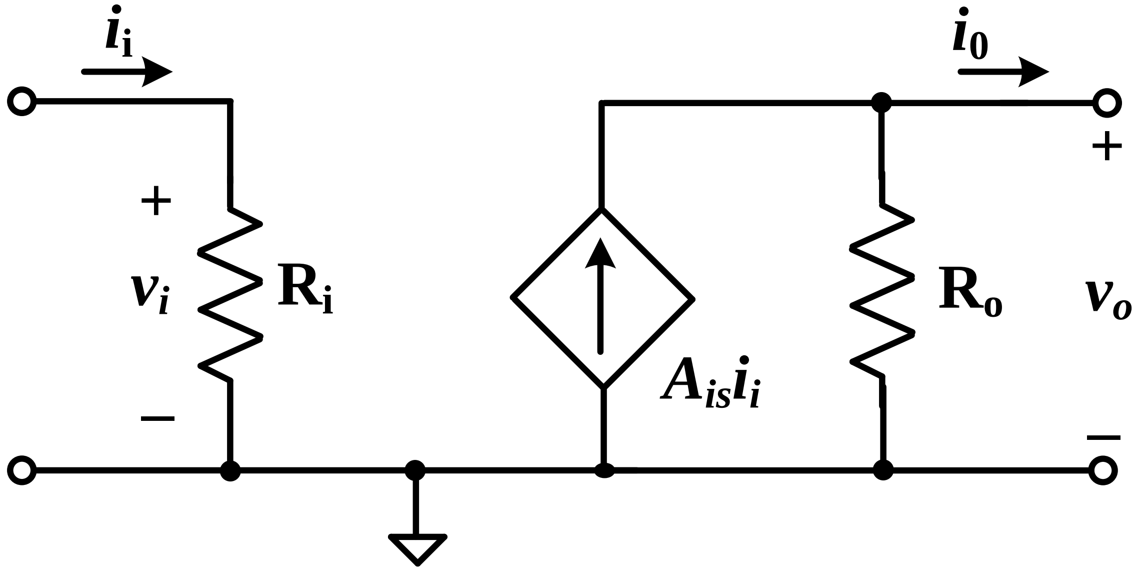
- DC power consumption: $P_{dc} = V_{CC} I_{CC} + V_{EE} I_{EE}$.
- In a single-supply amplifier, one of the two supply voltages is zero, i.e., the corresponding supply terminal is connected to the circuit ground.

2.2 Four Types of Single-Ended Amplifiers

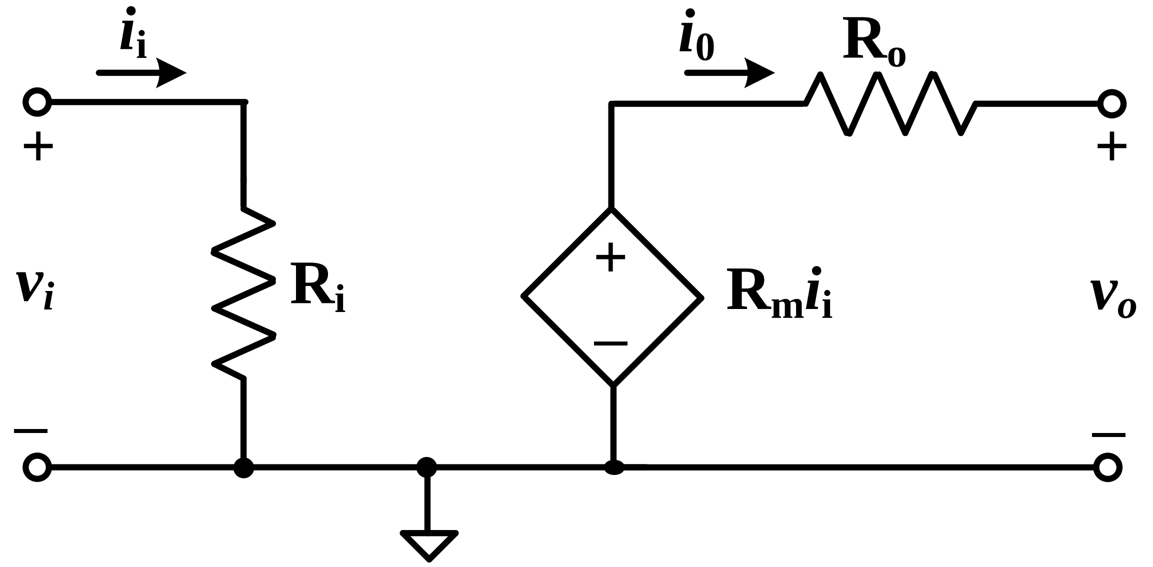
i) Voltage amplifier
(voltage input, voltage output)
Model: Voltage-controlled voltage source (VCVS).
Open-circuit voltage gain: A_{vo}.
Ideal VCVS: $R_i = \infty$, $R_o = 0$



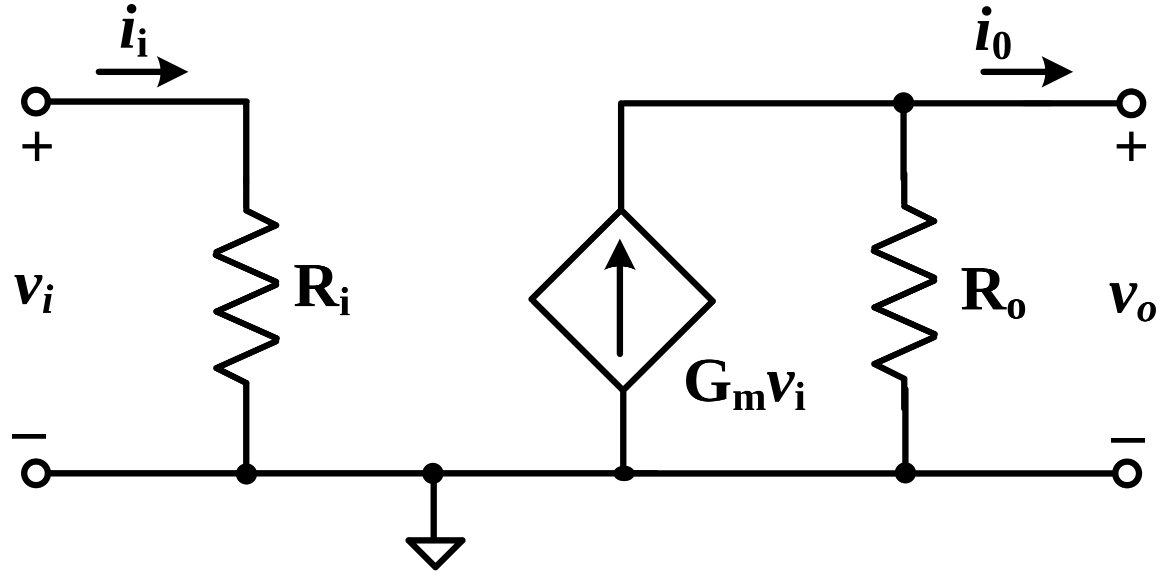
ii) Current amplifier
(current input, current output)
Model: Current-controlled current source (CCCS).
Short-circuit current gain: A_{is}
Ideal CCCS: $R_i = 0$, $R_o = \infty$



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: $R_i = \infty$, $R_o = \infty$.



2.3 Differential Signal

- A differential signal has two voltages (v_1, v_2) with reference to the circuit ground, with the information carried by the difference between the two voltages.
- It can be modeled using a common–mode (CM) voltage and a differential-mode (DM) voltage.

- CM & DM voltages from the terminal voltages:

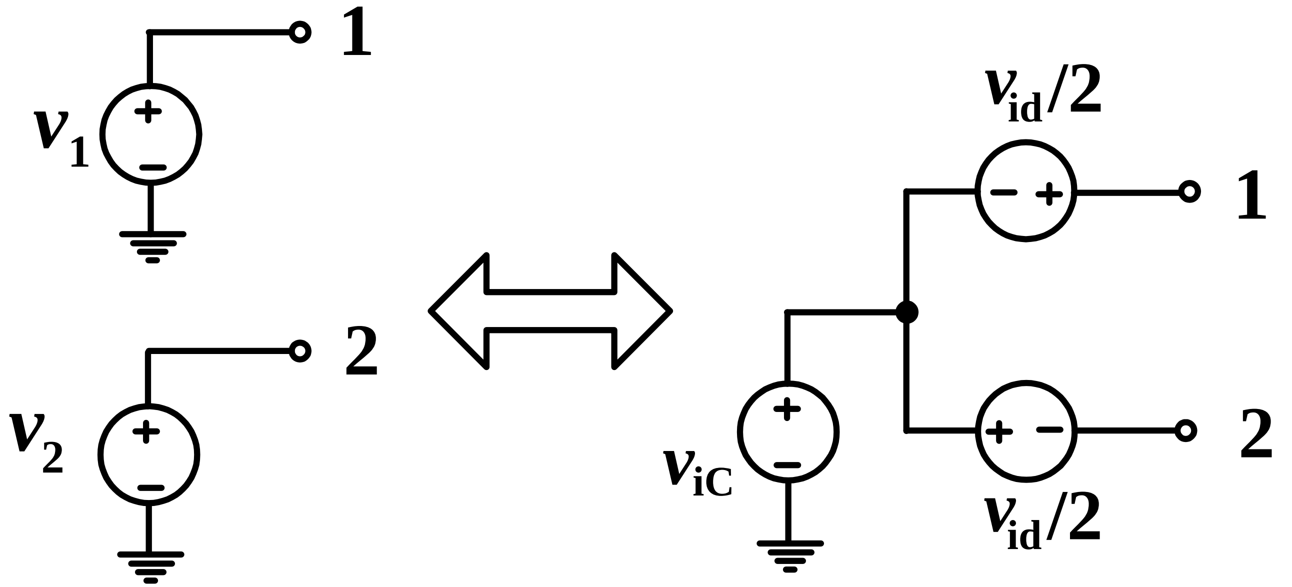
CM voltage: $v_{ic} = (v_1 + v_2)/2$

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

- Terminal voltages from the DM & CM voltages:

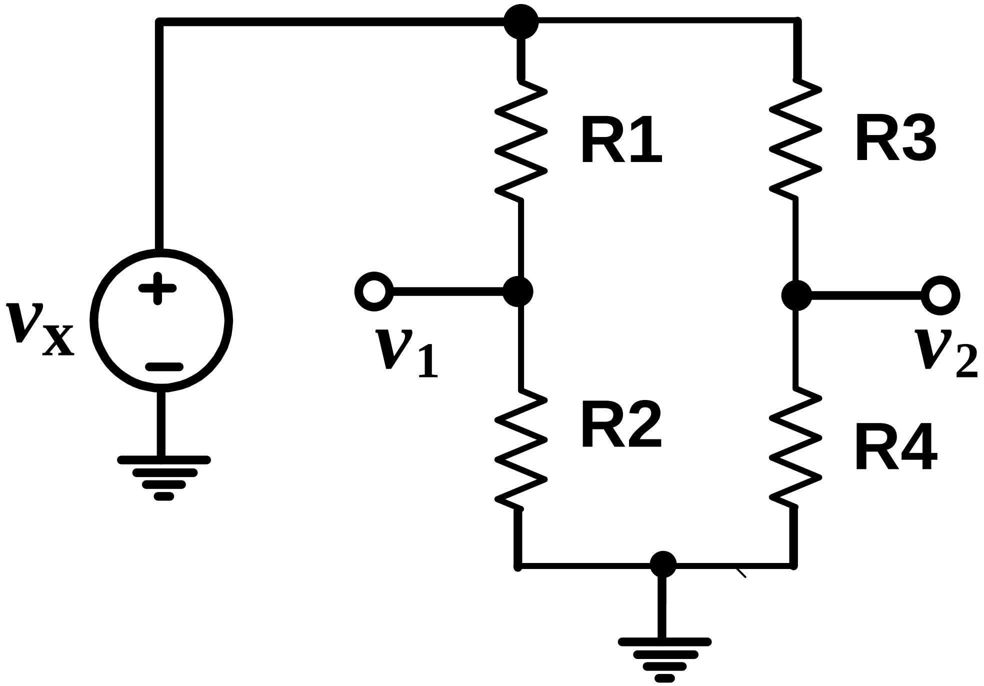
$v_1 = v_{ic} + v_{id}/2$

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



2.4 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 .



Let $R_1 = R_2$.

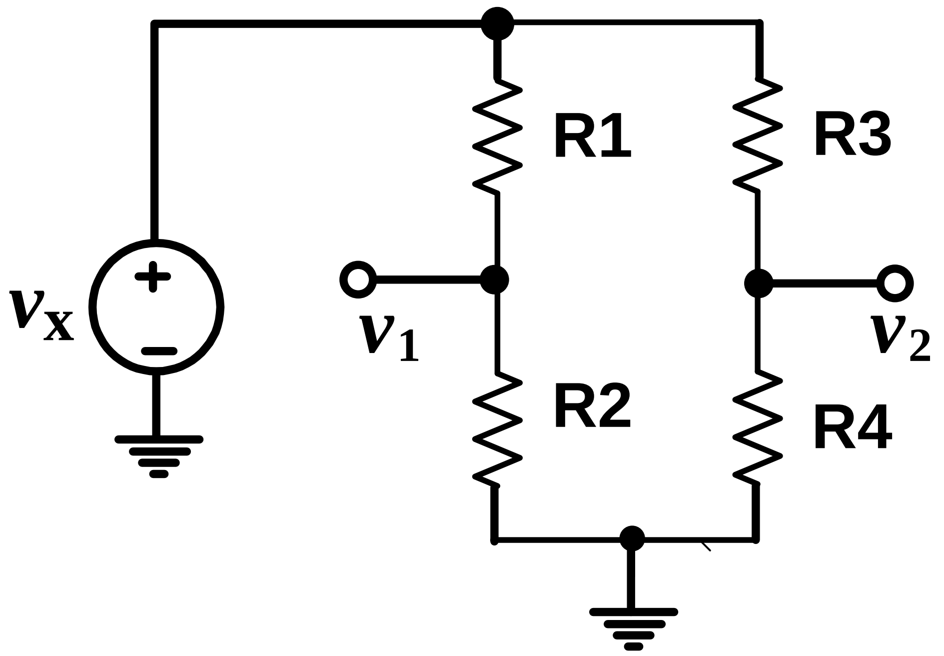
$$v_1 = \frac{R_2}{R_1+R_2} v_x = \frac{1}{2} v_x. \qquad v_2 = \frac{R_4}{R_3+R_4} v_x.$$

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: Let $R_3 = R_4(1+\delta)$.



$$v_1 = \frac{v_x}{2}. \qquad v_2 = \frac{R_4}{R_4(1+\delta)+R_4} v_x = \frac{v_x}{2+\delta}$$

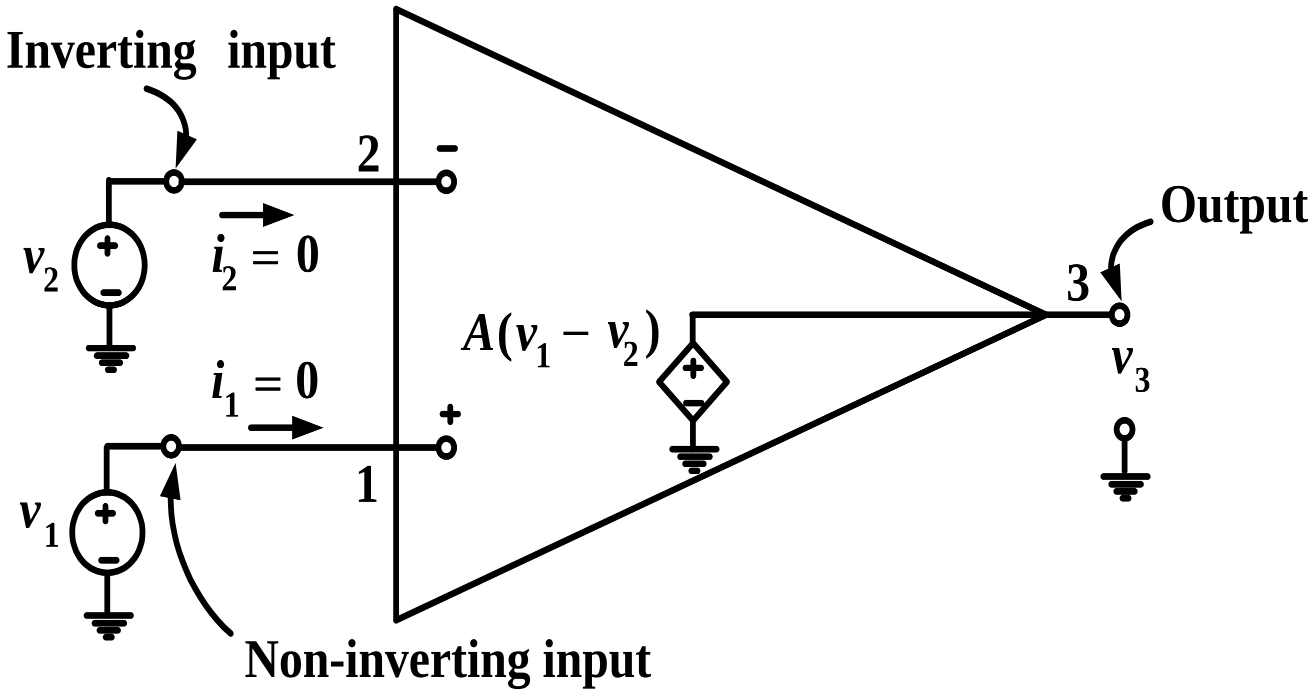
$$v_{ic} = \frac{v_1 + v_2}{2} = \frac{v_x}{2}\frac{1+\delta/4}{1+\delta/2} \approx (1-\frac{\delta}{4})\frac{v_x}{2}$$

$$v_{id} = v_1 - v_2 = \frac{v_x}{2}\frac{\delta/2}{1+\delta/2} \approx \frac{\delta}{4} v_x$$

- CM voltage is substantial. 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.

2.5 Differential Amplifier

- Differential input voltage & single-ended output voltage.
- Amplifies DM voltage, rejects CM voltage.
- DM input voltage: $v_{id} = v_1 - v_2$
- CM input voltage: $v_{ic} = (v_1 + v_2)/2$
- $v_1 = v_{\mathrm{ic}} + v_{id}/2$; $v_2 = v_{\mathrm{ic}} - v_{id}/2$.

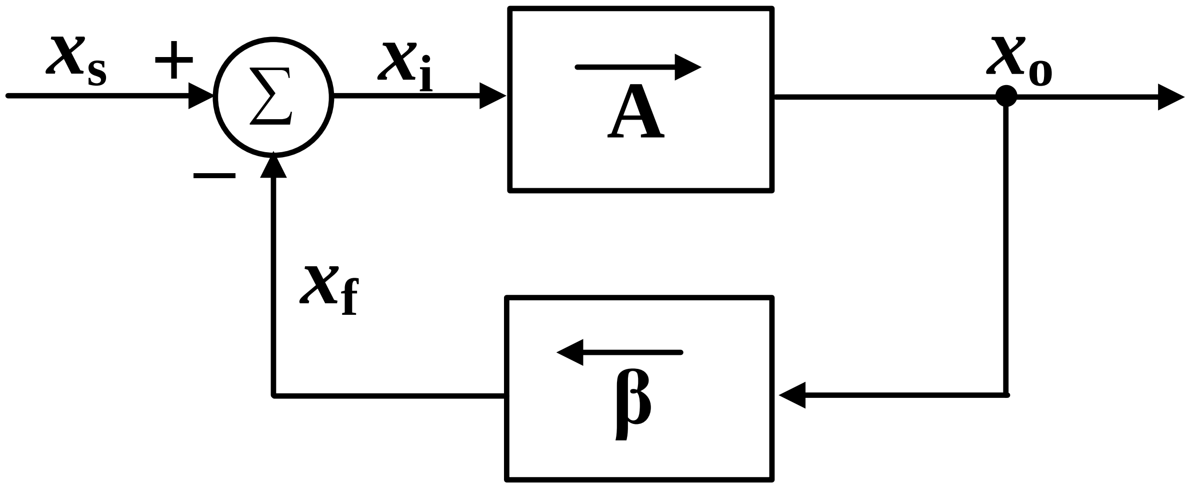


- *Ideal differential amplifier*
  - Zero input currents.
  - Completely rejects the CM voltage. Single-ended output voltage: $v_3 = A\, v_{id}$.

3. Feedback Amplifier

- **Feedback:** Addition of a fraction of the output to the input for desirable circuit behavior.
- **Negative feedback:** The output fraction addion 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 at the expense of gain reduction.
- **Positive feedback:** The output fraction increases the input. It is used to realize oscillators (function generators) & bi-stable (memory) circuits.
- **Negative & positive feedback combination:** It is used in filters (circuits with specific frequency response) for signal processing.

Negative 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.

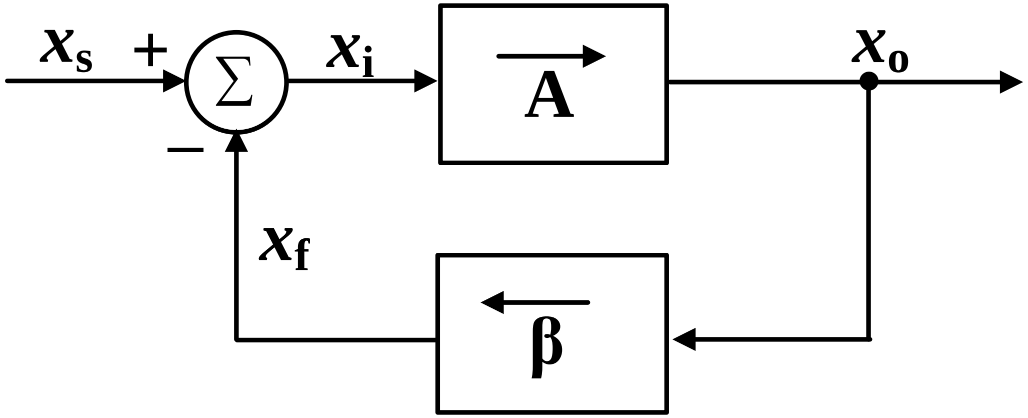
$$x_f = \beta\, x_o. \quad x_i = x_s - x_f. \quad x_o = Ax_i = A(x_s - \beta\, x_o) \Rightarrow x_o(1+A\beta) = Ax_s \Rightarrow x_o = Ax_s/(1+A\beta).$$

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

- Feedback amplifier gain (closed-loop gain)

  $$A_f = \frac{x_o}{x_s} = \frac{A}{1+A\beta}.$$

  For $A\beta \gg 1,\ A_f \approx \dfrac{1}{\beta}.$



- A may have large variability due to electronic device parameters. The circuit is designed such that β is determined by passive components and has a precise value.
- Example: $A = 10^3$ to 10^5 & $\beta = 1/10$.
  - $A = 10^3 \Rightarrow A_f = 10^3/(1+10^2) = 10/(1+10^{-2}) = 9.900.$
  - $A = 10^5 \Rightarrow A_f = 10^5/(1+10^4) = 9.999.$
- 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.

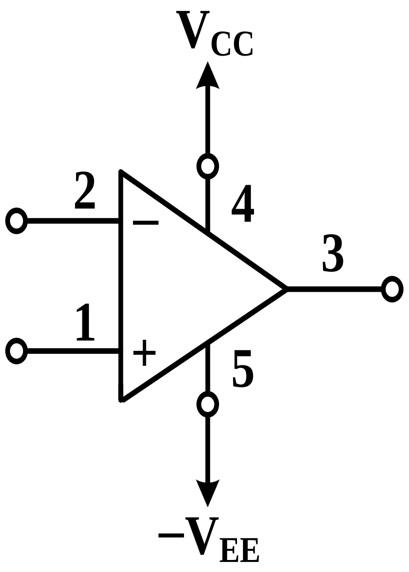
4. Operational Amplifier

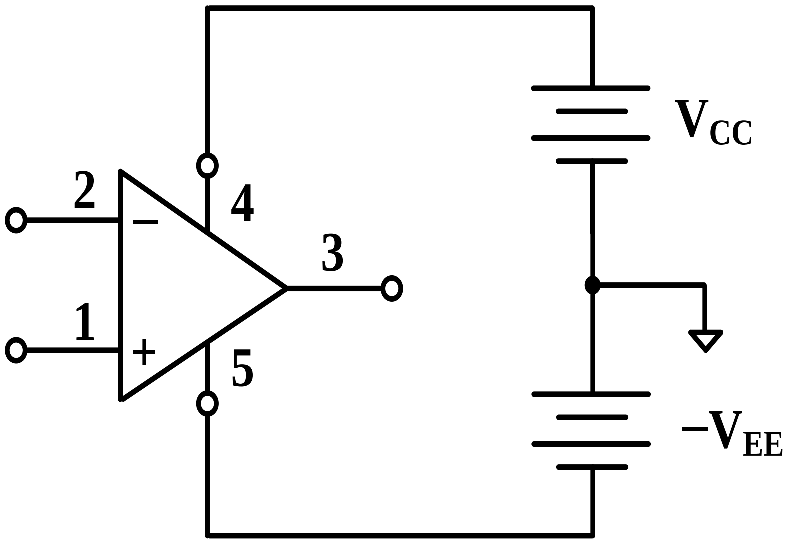
Operational amplifier (op amp, op-amp, or opamp) is a direct-coupled (dc) high-gain amplifier with differential voltage input & single-ended voltage output.

- Op amps were developed for mathematical operations on signal waveforms. The two inputs are very convenient for designing circuits with feedback.
- Op amp circuits are usually designed so that the circuit parameters are determined by passive components & nearly independent of electronic device parameters.
- Op amps are available as integrated circuits (ICs, electronic circuits with several internal passive & active devices on a single chip). A single IC may have several op amps and other circuits..

4.1 Op Amp Symbol & Supplies

- An op amp is a differential input voltage and single-ended output voltage amplifier with two supply terminals (+ve & −ve).
- The supplies are labeled 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 (left figure) or explicitly (right figure). The ground terminal is the common terminal of the two supplies, and the op amp does not have a ground 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.
- For simplifying the circuit schematic, supply connections are usually not shown.

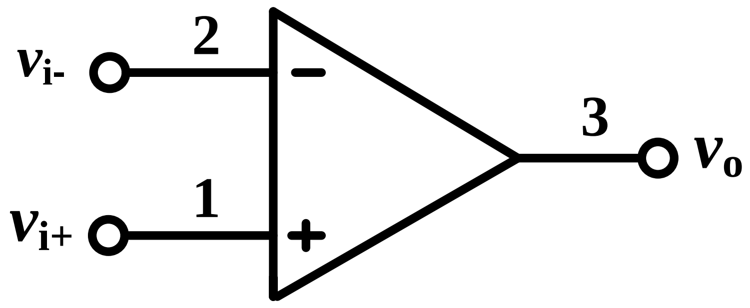
4.2 Simplified Op Amp Symbol & Pin Connections

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

  - non-inverting input terminal (1),

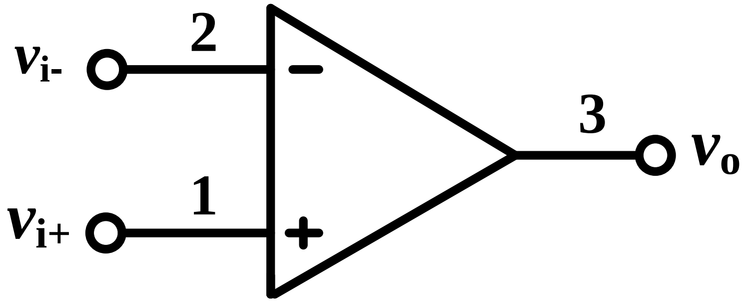
  - inverting input terminal (2),

  - output terminal (3).

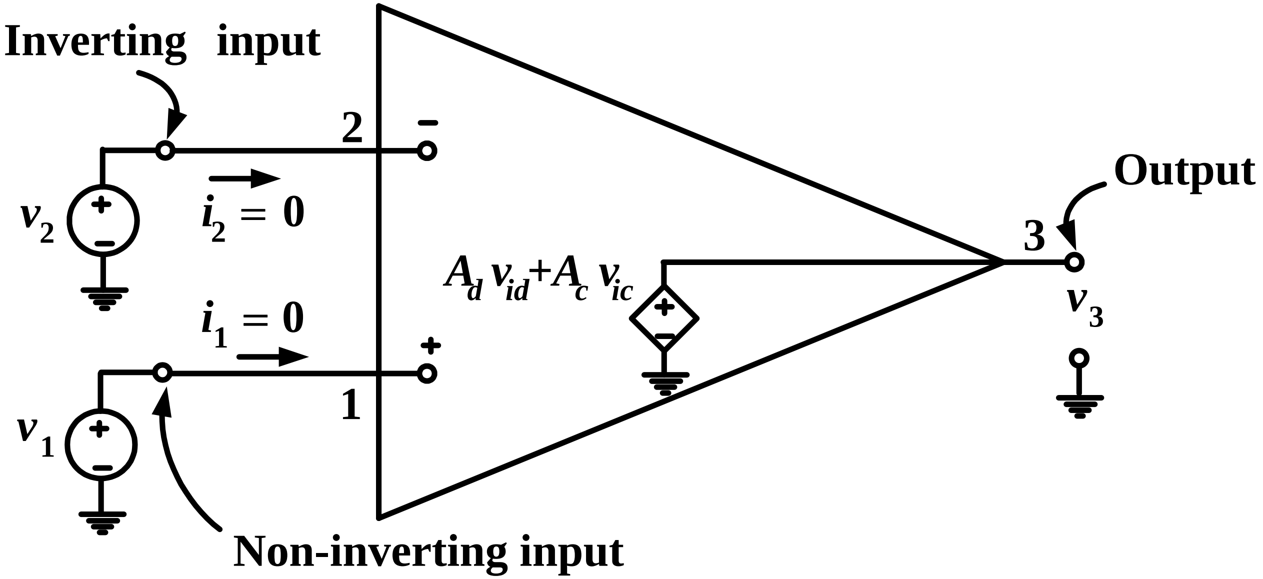


- The supply terminals are not shown in the simplified symbol. All terminal voltages are with reference to the circuit ground (Gnd), which is not shown in the symbol. The three terminals correspond to three single-ended ports:
  - non-inverting input port v_{i+}: $1-$ Gnd,
  - inverting input port v_{i-}: $2-$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 2 op amps (dual op-amp IC) $= 3 \times 2 + 2 = 8$.
- 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.



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

where A_d = DM gain, A_c = CM gain.

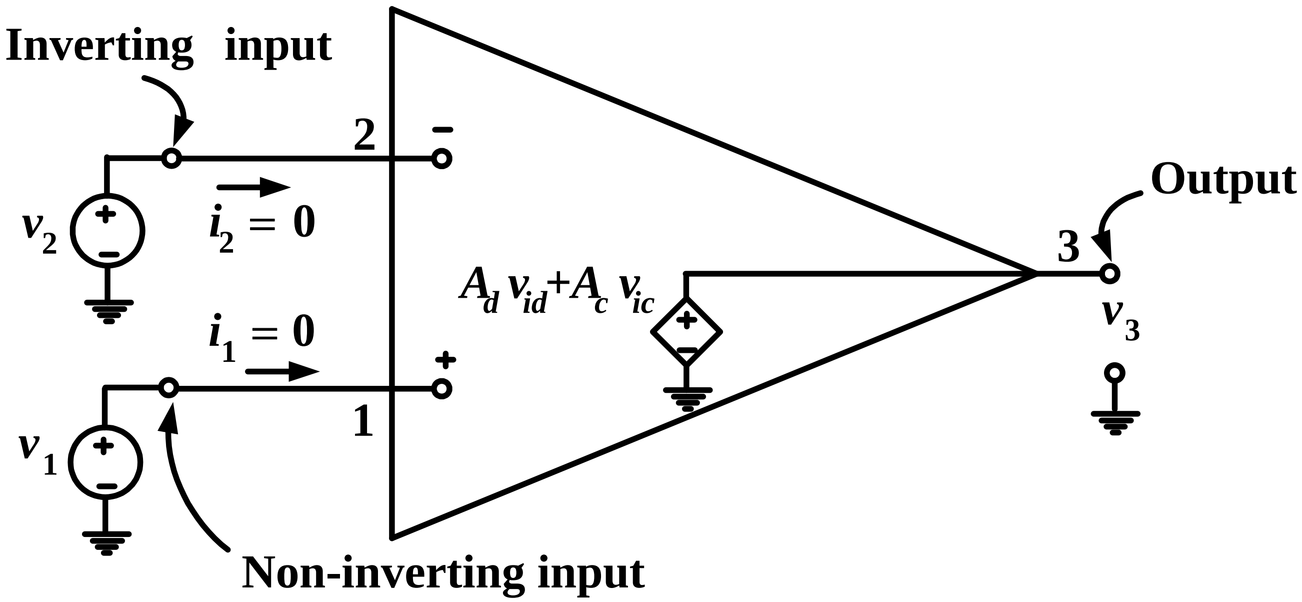
- Common-mode rejection ratio: CMRR $= A_d/A_c$.
- Ideal op amp
  - $A_d \to \infty$. $A_c \to 0$. $v_3 = A_d(v_1 - v_2)$. CMRR $= A_d/A_c \to \infty$.
  - Infinite input resistance for both inputs: zero input currents.

4.4 Linear Operation & Virtual Short

- 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.

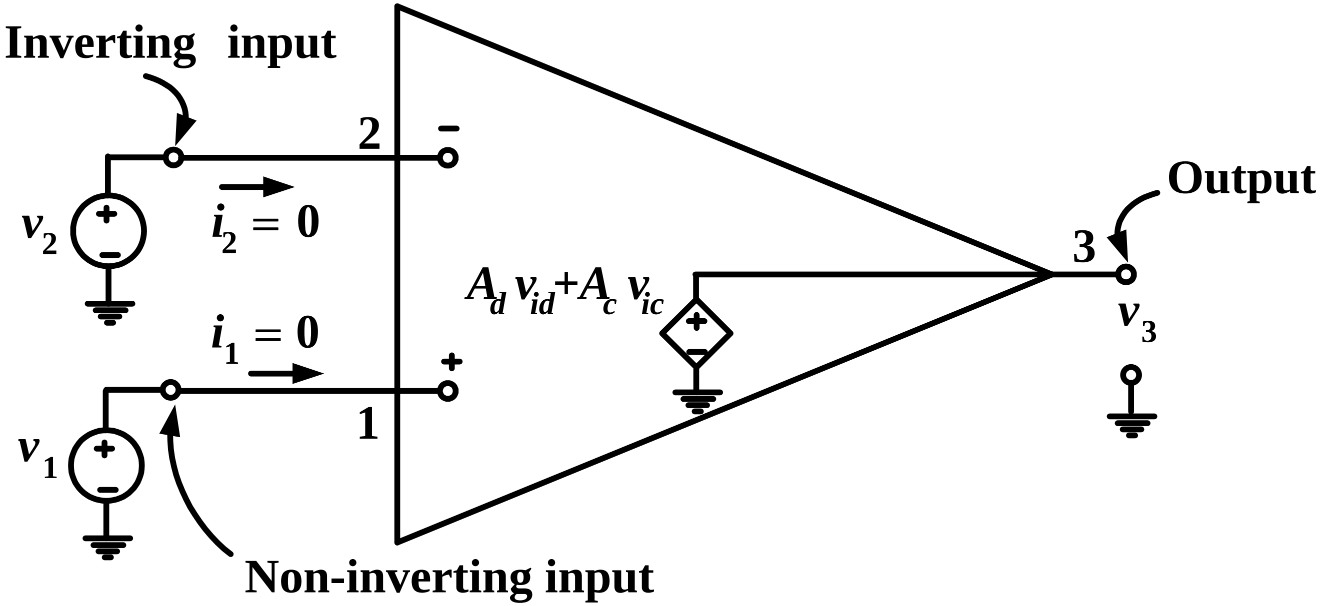


- Ideally, $A_d \to \infty$, $A_c \to 0$. For finite v_3, $v_{id} = v_3/A_d \to 0$.

  Also, input resistances R_{i1}, $R_{i2} \to \infty$, so the input currents i_1, $i_2 \to 0$.

  Thus, the voltage across the input terminals is zero ($v_{id} = 0$), and no currents flow into them ($i_1 = 0$, $i_2 = 0$). This condition is known as a *virtual short* across the input terminals.

- Virtual short across the input terminals: $v_{id} = 0$, $i_1 = i_2 = 0$. (An actual short has zero voltage and arbitrary current).
- Virtual short is a very useful concept in analyzing linear op amp circuits.

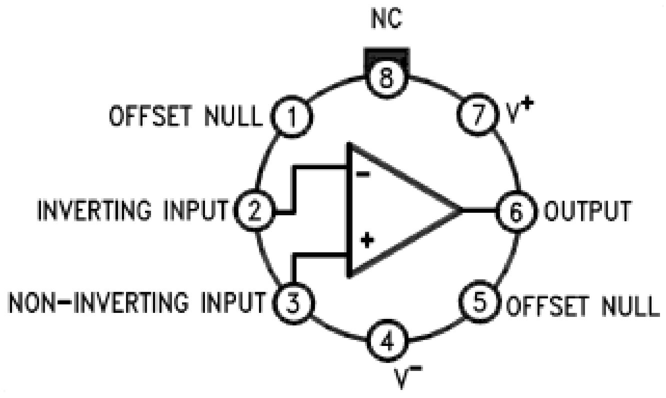


- Virtual short assumption is applicable only during linear operation of the op amp.
- The conditions for linear operation are to be satisfied by external circuit & input voltages.
- During an op amp's nonlinear operation, the input currents may increase, and the output is distorted.

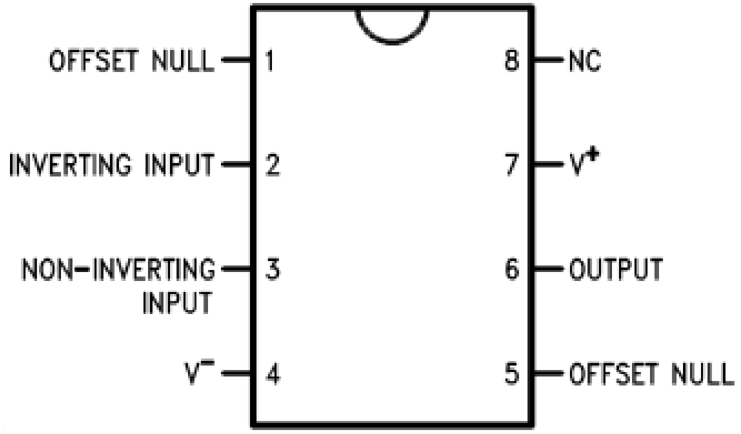
4.5 Op Amp Example: General-Purpose Op Amp LM741

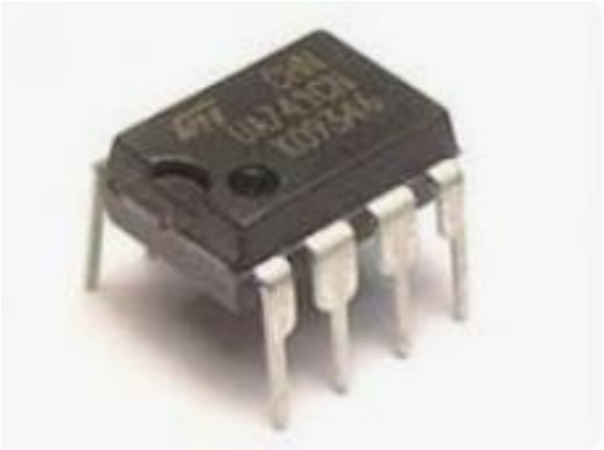
- Supply: ± 10 V to ± 18 V, ± 15 V typical.
- $A_d > 50\times 10^3$.
- For ± 15 V supply, Input range: ± 12 V. Output swing: ± 12 V.
- Output short-circuit current: 25 mA.
- Power consumption < 100 mW.

LMC Package
8-Pin TO-99
Top View



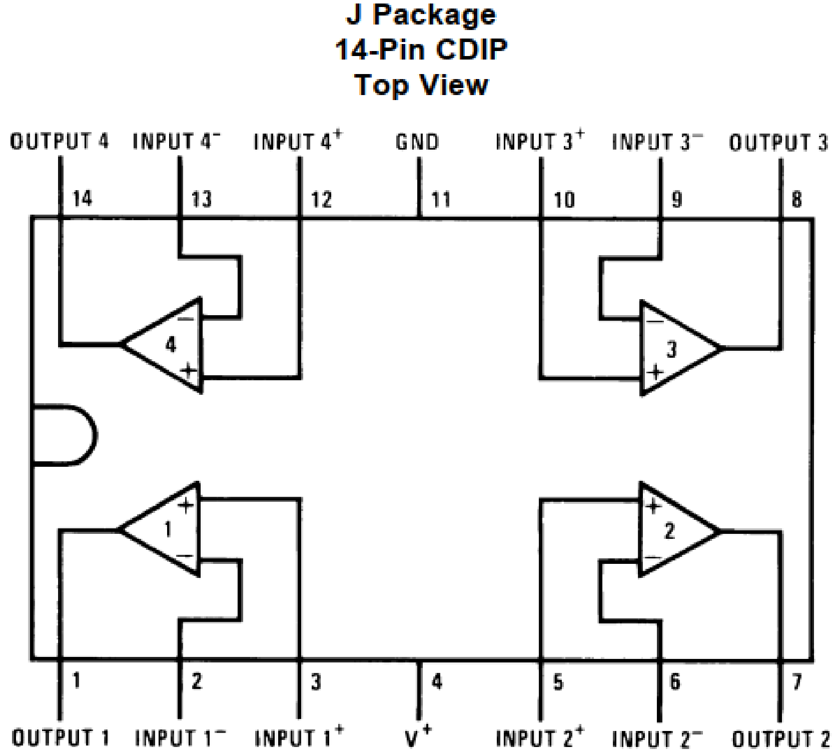
NAB Package
8-Pin CDIP or PDIP
Top View

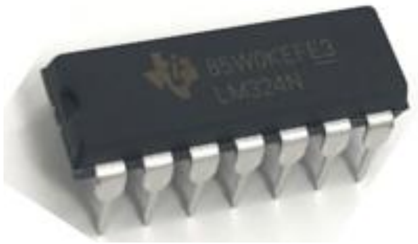




4.6 Op amp Example: Low-Power Quad Operational Amplifiers LM324

- IC with 4 independent op amps. Shared supply pins (V+, Gnd).
- Supply: $\pm$1.5 V to $\pm$16 V, $\pm$2.5 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 mW.

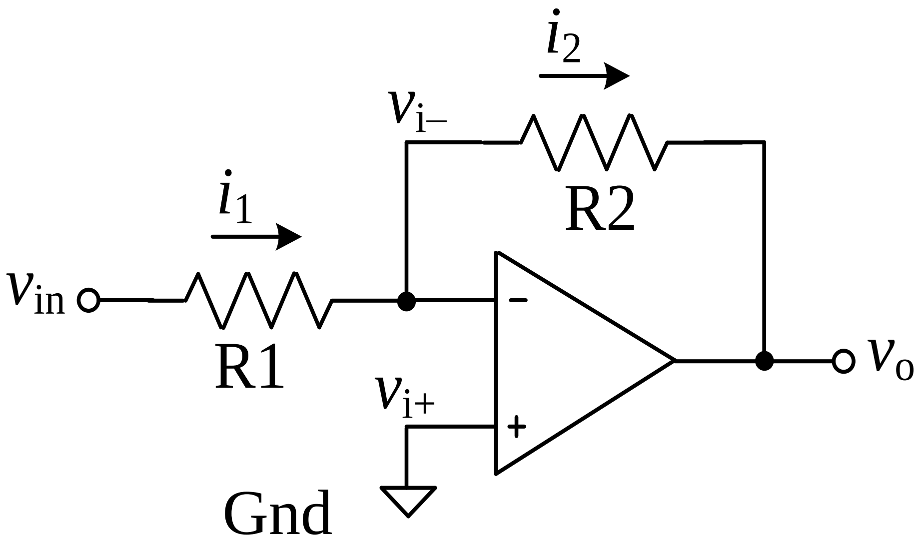




5. Linear Circuits

- 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



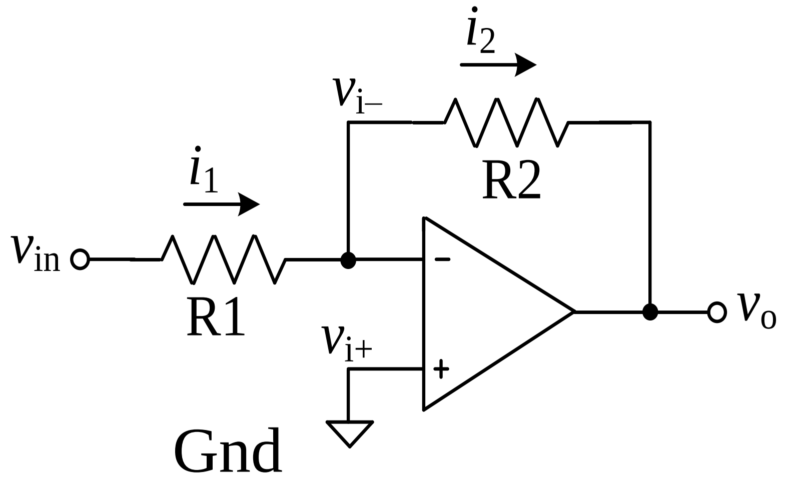
- $v_{i+} = 0$.

Assume virtual short across the op amp inputs: $v_{i-} = v_{i+}$ & $i_1 = i_2$.

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

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

- 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 Gnd.
- Current gain & power gain depend on the load resistance (not shown) connected between the output and Gnd.



- 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.

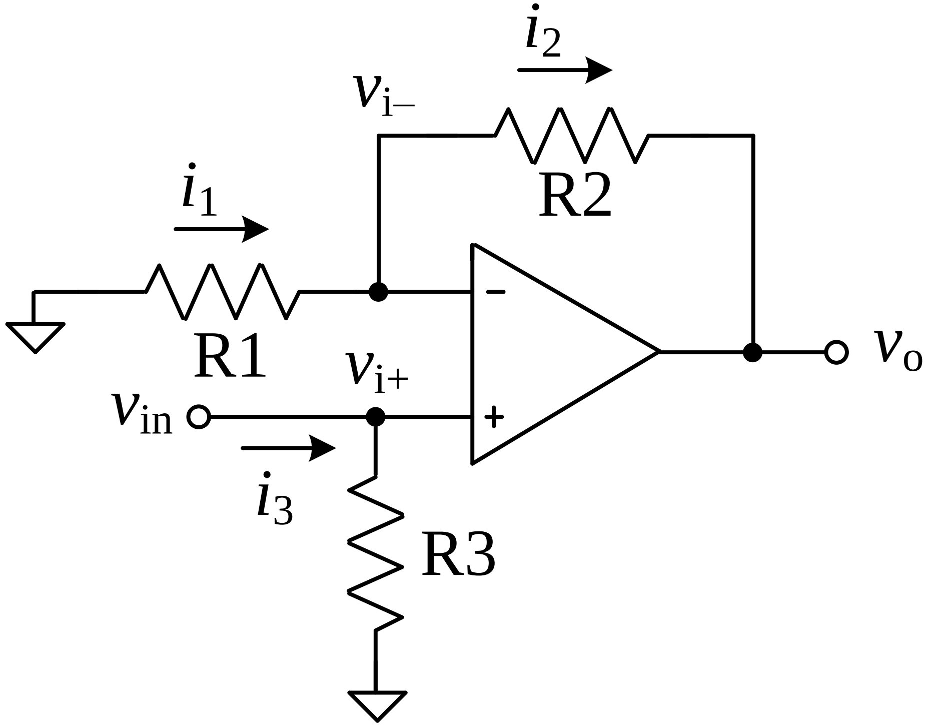
  Same can be seen for $v_{i-}\downarrow$.
- It can be seen that the virtual short is violated if the input terminals are interchanged.
- Application: Precise inverting gain with low to moderate R_{in}.
- Example: $R_1 = 10\ \text{k}\Omega$, $R_2 = 100\ \text{k}\Omega$, $R_L = 1\ \text{k}\Omega$.

  $A_v = -R_2/R_1 = -10.$ $\quad\quad R_{in} = R_1 = 10\ \text{k}\Omega$.

  $A_i = i_o/i_1 = (v_o/R_\text{L})/(v_{in}/R_1) = (v_o/v_{in})(R_1/R_\text{L}) = -R_2/R_L = -100.$

  $A_p = A_v A_i = (-10)(-100) = 1000.$

5.2 Non-inverting Amplifier



- $v_{i+} = v_{in}$

  Assume virtual short across the op amp inputs: $v_{i-} = v_{i+}$ & $i_1 = i_2$

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

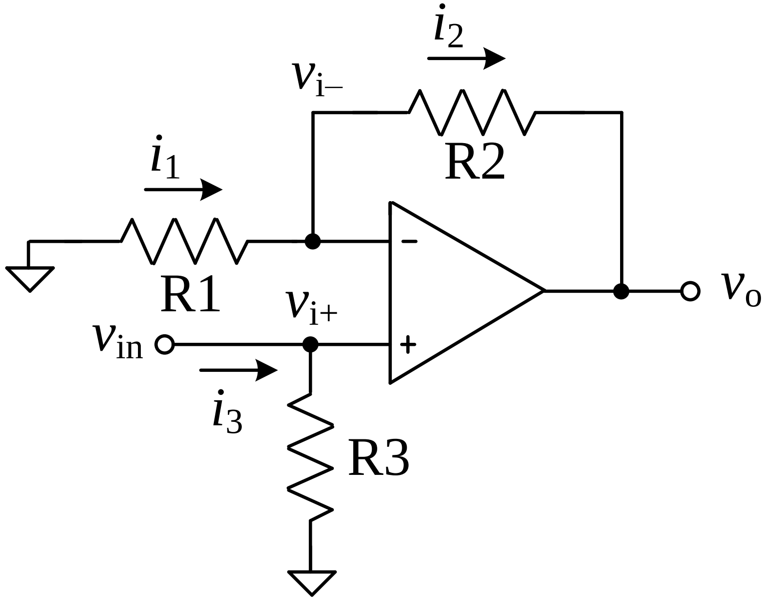
  $v_o = v_{i+} - R_2\, i_2 = (1 + R_2/R_1)\, v_{in}$
- Voltage gain: $A_v = v_o/\, v_{in} = 1 + R_2/R_1$
- Input resistance: $R_{in} = v_{in}/i_3 = R_3$
- R3 is optional & selected for the desired R_{in}.
- Current & power gains depend on the load resistance (not shown).

- 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 can be seen for $v_{i-}\downarrow$.



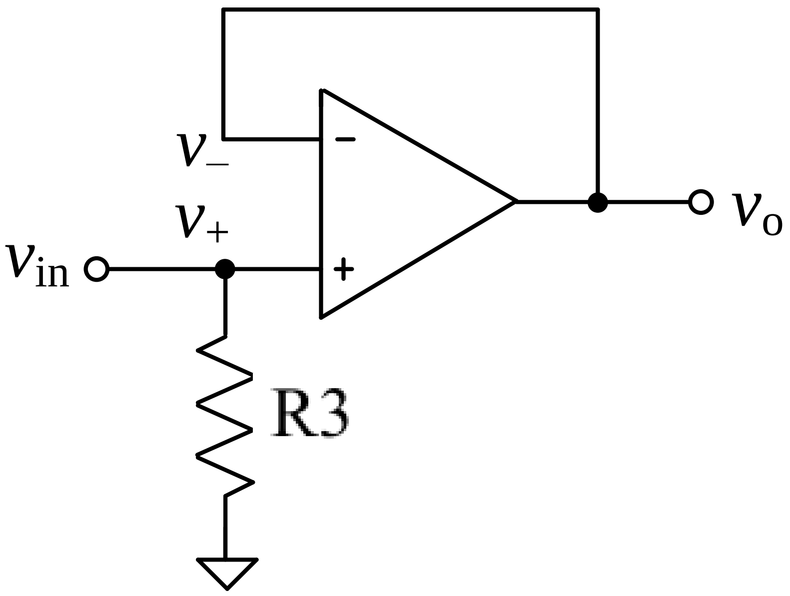
- It can be seen that the virtual short is violated if the input terminals are interchanged.
- *Application:* Precise noninverting gain with high, moderate, or low R_{in}.
- Example: $R_1 = 10\ \text{k}\Omega$, $R_2 = 100\ \text{k}\Omega$, $R_3 = 1\ \text{M}\Omega$, $R_L = 1\ \text{k}\Omega$.

  $A_v = v_o/v_{in} = 1 + R_2/R_1 = 11.$ $\qquad\qquad R_{in} = R_3 = 1\ \text{M}\Omega.$

  $A_i = i_o/i_3 = (v_o/R_\text{L})/(v_{in}/R_3) = (v_o/v_{in})(R_3/R_\text{L}) = (11)(10^6/10^3) = 11 \times 10^3.$

  $A_p = A_v\,A_i = (11)(11000) = 121 \times 10^3.$

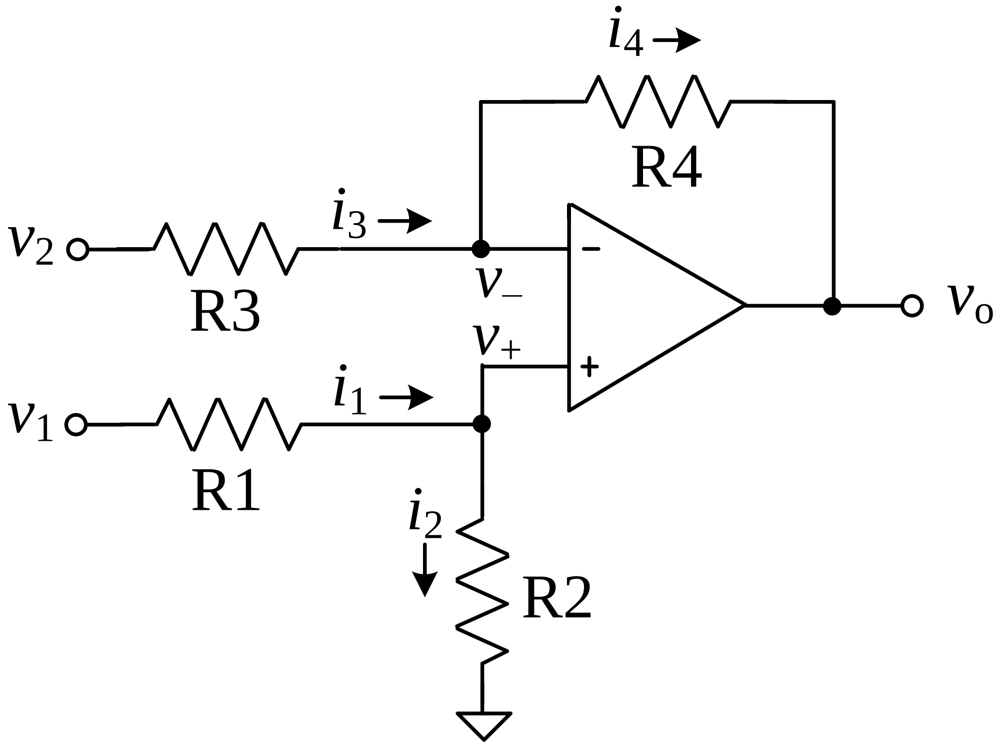
5.3 Unity Follower (Unity Buffer)



- 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: $R_{in} = R_3$.
- R3 is optional, it is selected for a desired R_{in}.
- The circuit provides unity voltage gain. Current and power gain depend on the load resistance.

• *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 acroos the op amp inputs:

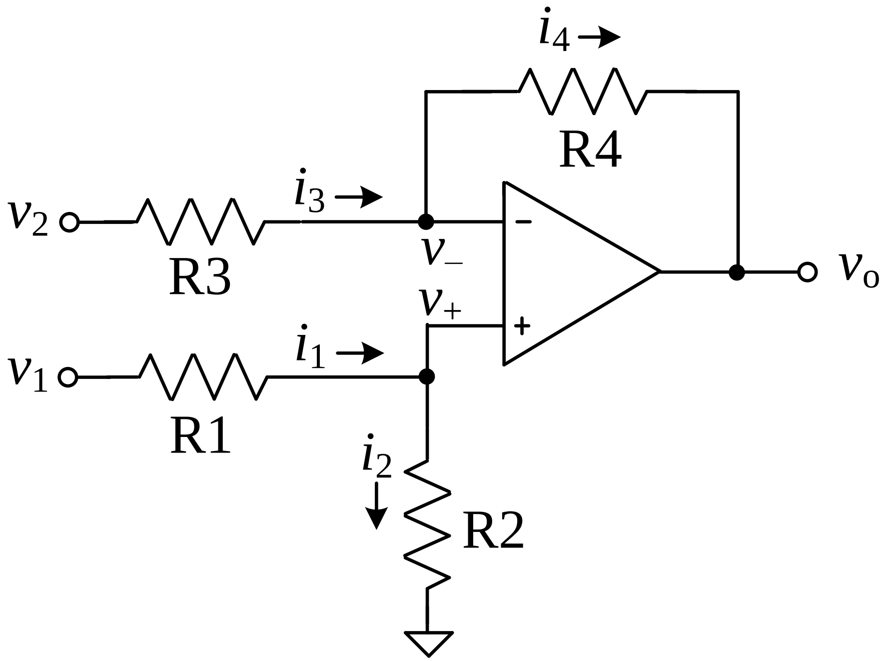
  $i_1 = i_2$ & $i_3 = i_4$. $v_{i+} = v_{i-}$.
- Use the superposition method. Find voltage gain & input resistance for each input by setting the other input as 0.

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

- **Output voltage**

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

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



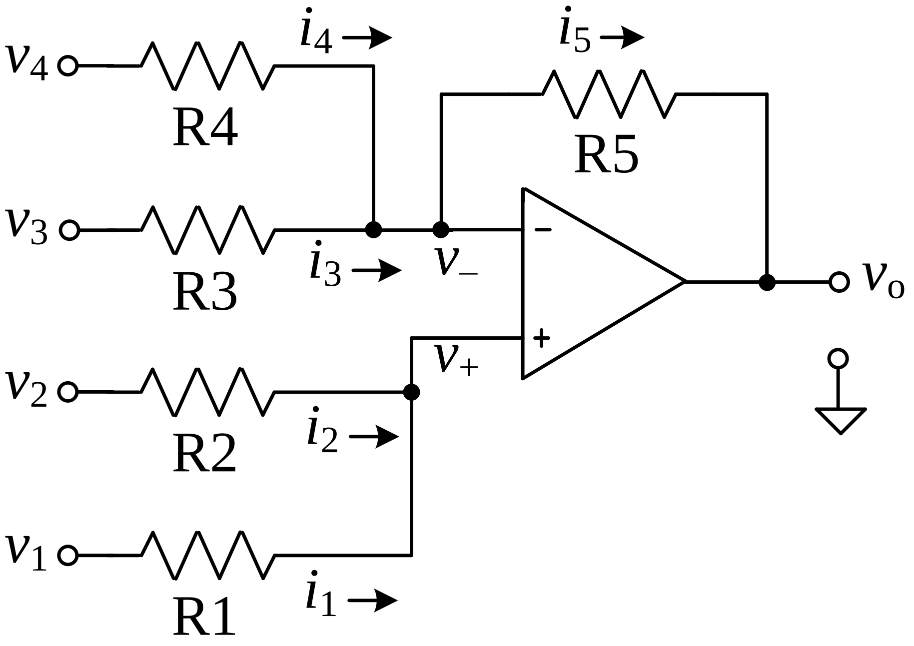
- DM gain $A_d = \alpha$. CM gain $A_c = 0$.
- $R_{in1} = R_1 + R_2$. $R_{in2} = R_3$.

- 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 across op amp inputs: 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.

- $v_o = A_1 v_1 + A_2 v_2 + A_3 v_3 + A_4 v_4$

$v_2 = v_3 = v_4 = 0$: $A_1 = [v_o / v_1] = [R_2/(R_1+R_2)]\,[1 + R_5/(R_3 \parallel R_4)]$. $R_{in1} = [v_1 / i_1] = R_1 + R_2$,

$v_1 = v_3 = v_4 = 0$: $A_2 = [v_o / v_2] = [R_1/(R_1+R_2)]\,[1 + R_5/(R_3 \parallel R_4)]$. $R_{in2} = [v_2 / i_2] = R_1 + R_2$.

$v_1 = v_2 = v_4 = 0$: $A_3 = [v_o / v_3] = -R_5 / R_3$. $R_{in3} = [v_3 / i_3] = R_3$.

$v_1 = v_2 = v_3 = 0$: $A_4 = [v_o / v_4] = -R_5 / R_4$. $R_{in4} = [v_4 / i_4] = R_4$.

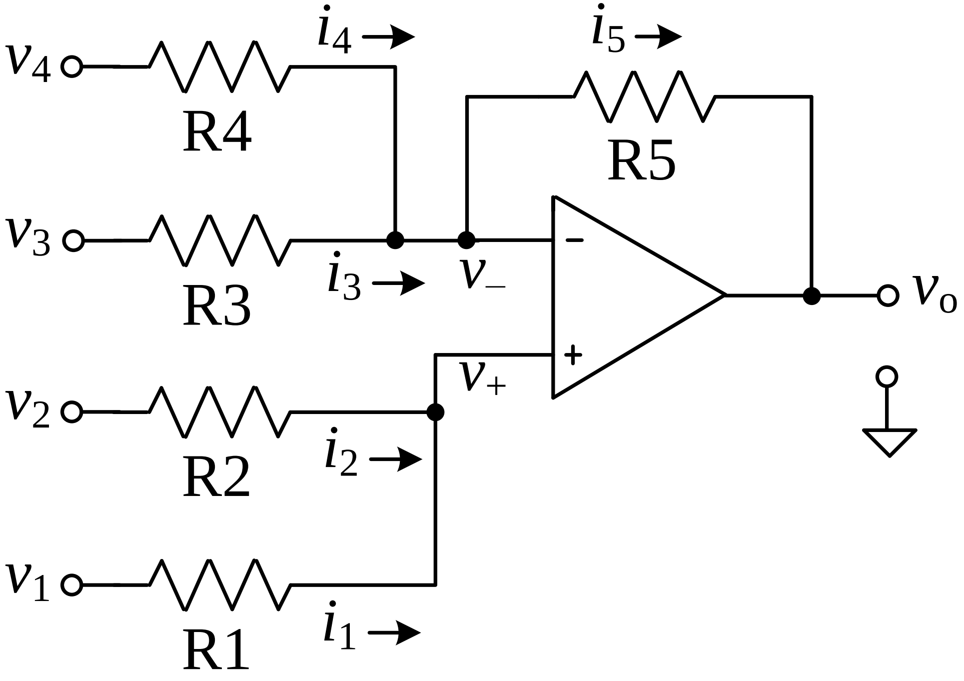
- Voltage gains for 4 inputs

$A_1 = [v_o / v_1] = [R_2/(R_1+R_2)]\ [1+ R_5/(R_3 \| R_4)]$.

$A_2 = [v_o / v_2] = [R_1/(R_1+R_2)]\ [1+ R_5/(R_3 \| R_4)]$.

$A_3 = [v_o / v_3] = -R_5 / R_3$.

$A_4 = [v_o / v_4] = -R_5 / R_4$.



- The circuit provides convenient inverting gain controls, independently by R_3 & R_4, together by R_5. Non-inverting gain controls are more difficult. Therefore, inverting summation is preferred for variable gains.
- The circuit can be extended for multiple inputs.

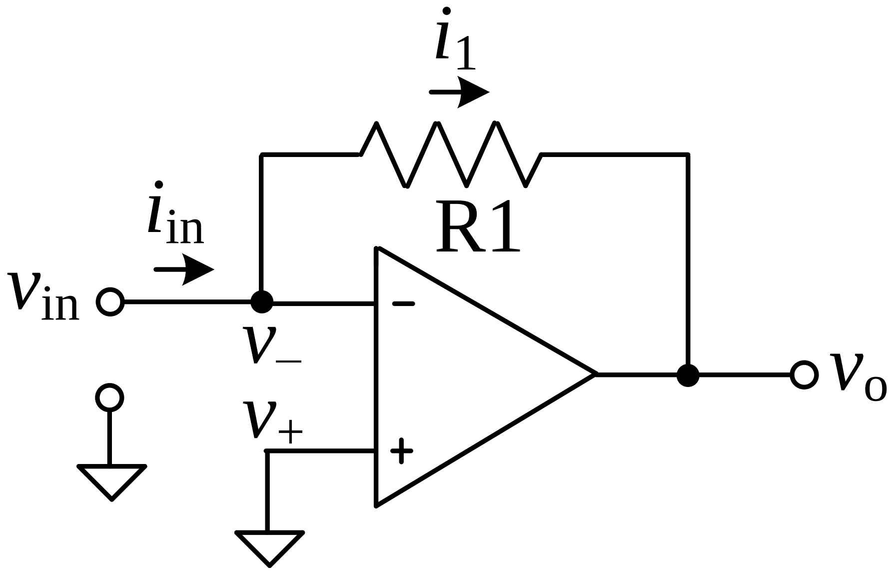
5.6 Current-to-Voltage (I/V) Converter (Trans-resistance Amplifier)

- Virtual short across the op amp inputs:

  $v_{i-} = v_{i+} = 0. \quad i_1 = i_{in}.$

  Therefore, $v_O = v_{i-} - R_1 i_{\text{in}} = - R_1 i_{\text{in}}$

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

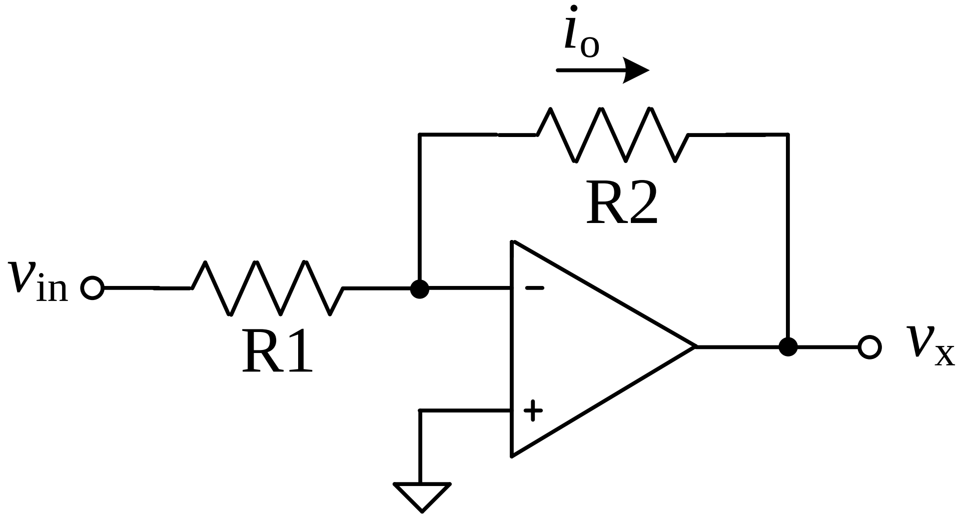


- Application: I/V converter for input current with ground as the return.

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

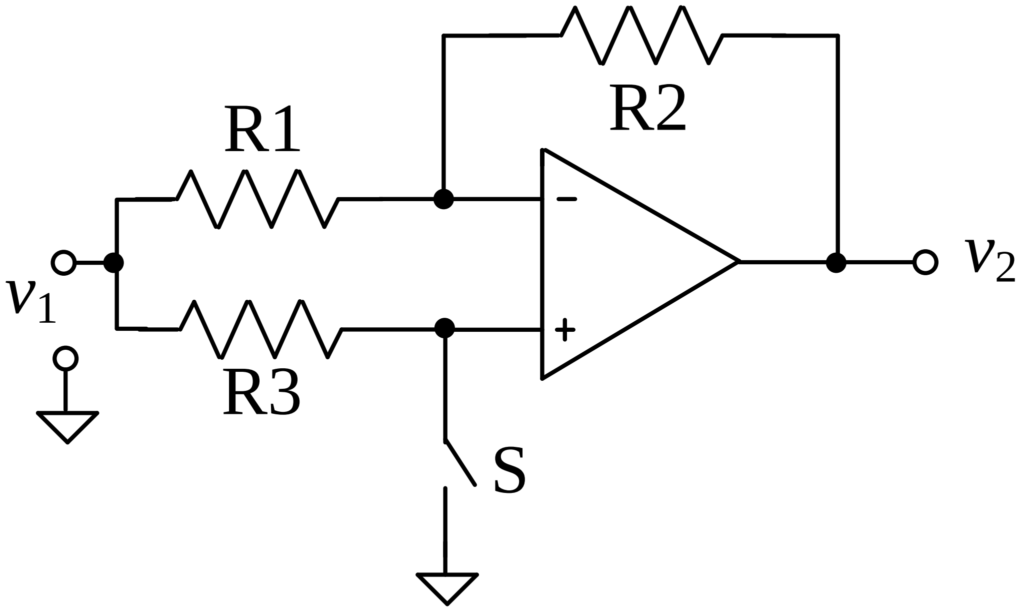
- Re-purposed inverting amplifier circuit, for output current in load R2.

  $i_O = v_{in}/R_1$. $R_{in} = R_1$. $v_X = -R_2\, i_O$.
- R_2 is limited by voltage swing at v_X.
- 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 C 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. $R_1 = R_2$.
- 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 circuits.

5.9 AC Amplifier

- 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 amplifier, each using a single capacitor, as 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 the circuit ground.

- *AC Amplifier Examples*

  The inverting and non-inverting dc amplifiers are converted to 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}.

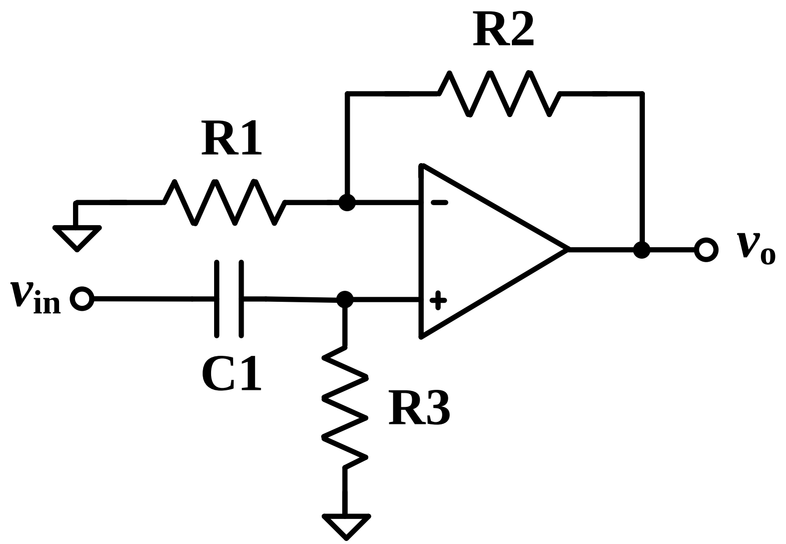
- *AC Non-inverting Amplifier*

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

  $f_c = 1/(2\pi R_3 C_1)$

  For $f \gg f_c$,

  $A_v = 1 + R_2/R_1$. & $R_{in} = R_3$



Op amp inputs need a small DC current, known as input bias current. R3 provides the DC current path for the non-inverting input; R1 and R2 for the inverting input.

- *AC Inverting Amplifier*

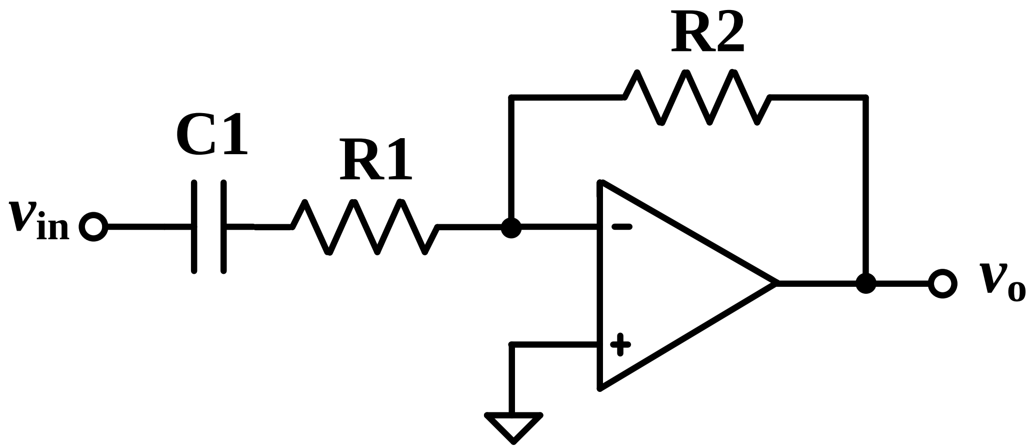
  C_1 selection: $1/(2\pi\, f_{min} C_1) \ll R_1$

  $f_c = 1/(2\pi\, R_1 C_1)$

  For $f \gg f_c$,

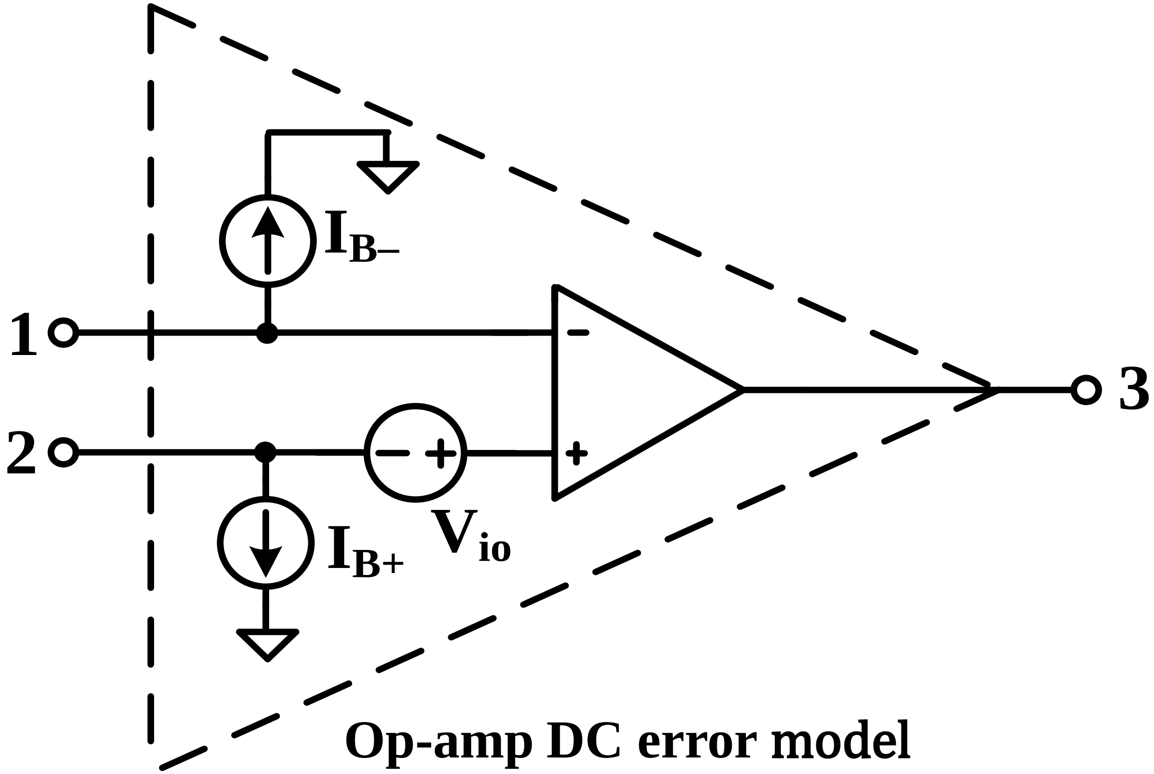
  $A_v = -R_2/R_1$ and $R_{in} = R_1$

  Op amp inputs need a small input bias current. The non-inverting input has direct connection to Gnd, and R2 provides DC path for the inverting input.



6. Practical Op Amp

- For linear operation, the two input voltages, output voltage, and output current should be within the specified limits (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) that must be permitted by external circuit.

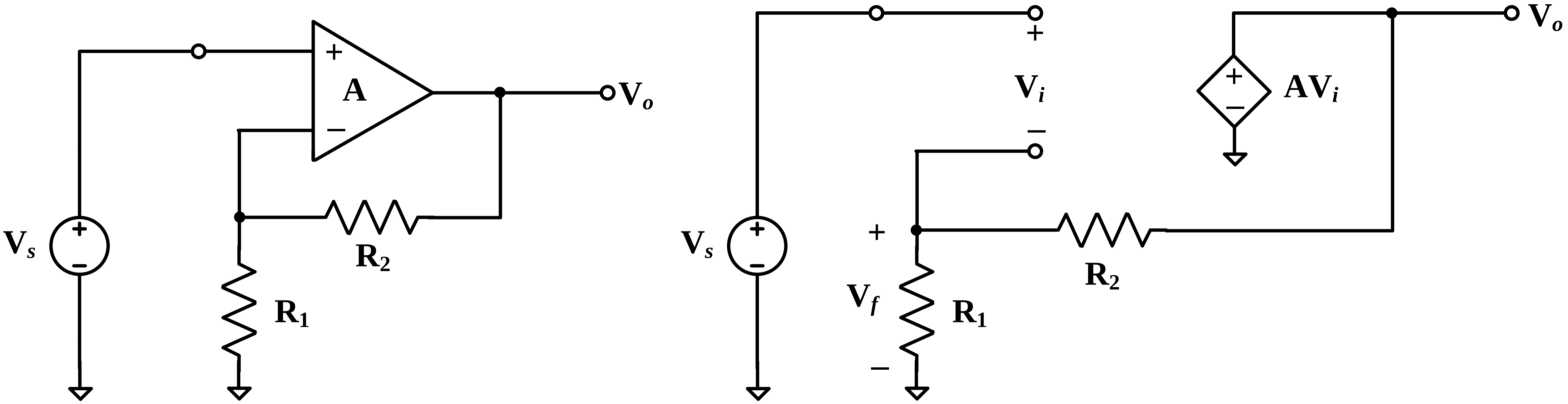


Op-amp DC error model

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

7. Non-inverting Amplifier as a Negative Feedback Amplifier

- In the non-inverting amplifier, feedback is applied at the inverting input, subtraction uses the op-amp differential input, the op-amp differential gain is the open-loop gain A, and the feedback factor β is set by the resistive attenuator (R1, R2).



- Open-loop gain = op-amp differential gain = A.
- Feedback factor β is set by R1 & R2. It has negligible variation compared with A.

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

- A_f is precise for $A_f \ll A$. Thus, the gain precision is at the expense of gain reduction.
- Other features (based on further analysis) include 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 Comparator

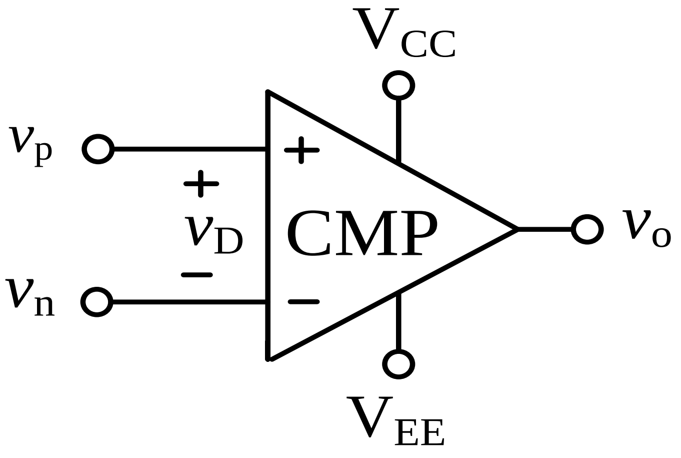
- An op amp like device for open-loop operation & precise binary output levels.

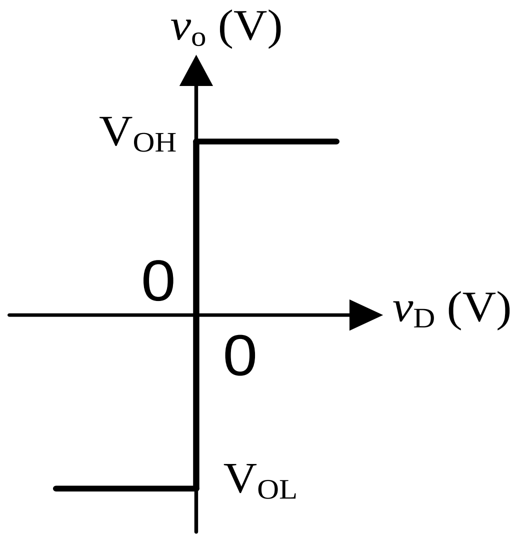
- Circuit symbol: op amp symbol.

- Analog inputs & binary output.

- Input swing and output levels depend on the internal circuit and supply voltages (V_{CC+}, V_{EE-}).

- Transfer characteristic: very high gain at $v_d \approx 0$ with sharp transition between the two output levels.



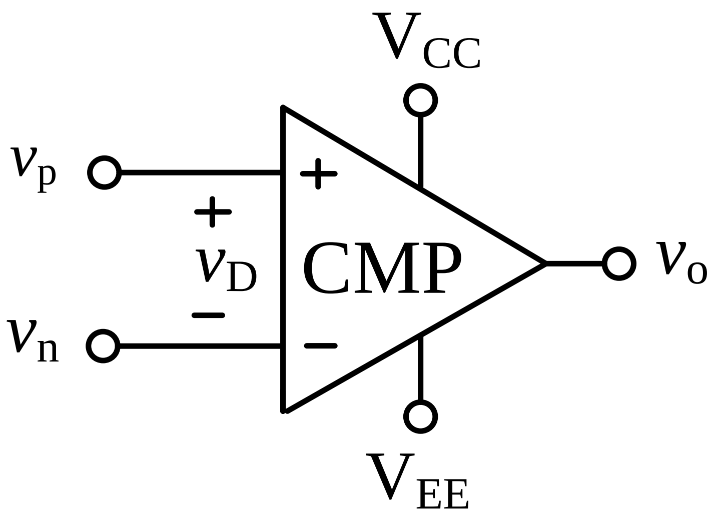


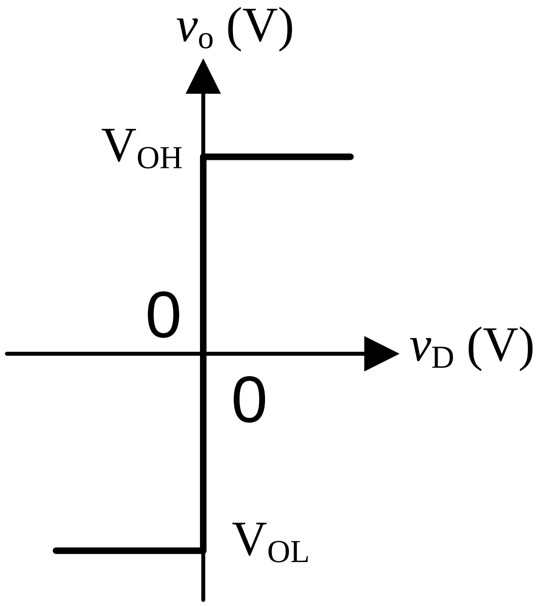
$v_p > v_n \Rightarrow v_d > 0 \Rightarrow v_o = V_{OH}$ (high-level),

$v_p < v_n \Rightarrow v_d < 0 \Rightarrow v_o = V_{OL}$ (low-level),

$v_p \approx v_n \Rightarrow v_d \approx 0 \Rightarrow$ sharp transition between V_{OL} and V_{OH}.

- A comparator is designed for very low input currents despite large differential input voltage.
- An op amp can also be used as a comparator with due consideration for input current limiting.





- Comparators are among the key devices for interfacing the analog & digital circuits.

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