EE Dept, IIT Bombay
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Course: MS101 Makerspace
EE Lectures: 04 & 05

Operational Amplifier Circuits

Topics: Signal basics; Amplifiers; Op-amps; Linear circuits; Feedback amplifier & oscillator; Nonlinear circuits.

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, D Chakraborty, K Chatterjee, BG Fernandes, J John, DK Sharma, NS Shiradkar, KR Tuckley

1. Signal Basics

Signal: 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: Disturbance unrelated to the signal.

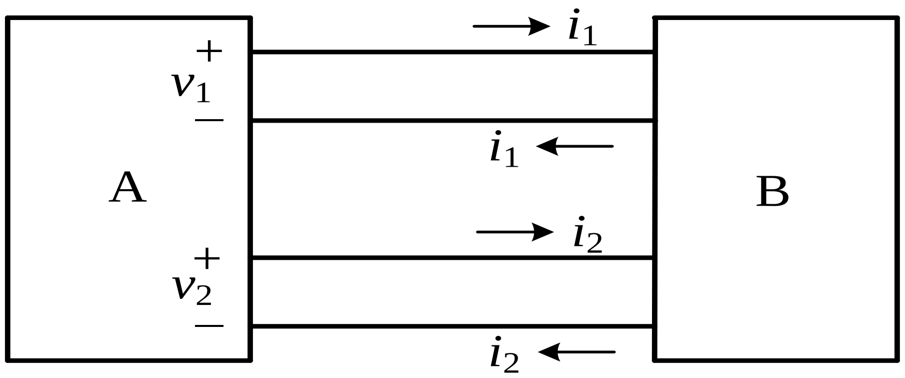
Distortion: Disturbance related to the signal.

Differential signals: Each signal needs two conductors.

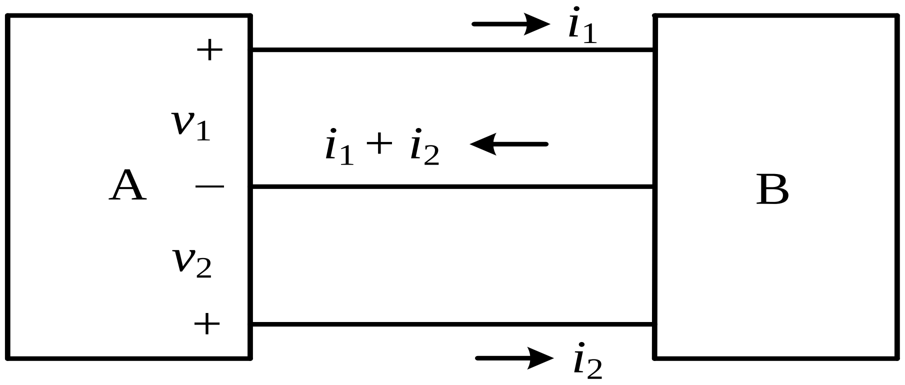
Single-ended signals: Several signals share a common reference in the case of voltage signals, & a common return in the case of current signals.

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.



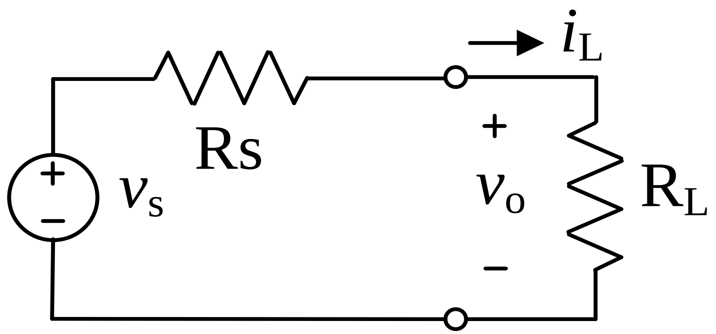
Two differential signals (each with two conductor)



Two single-ended signals (common reference & return)

Two signal representations

Voltage source model
(Thevenin form)

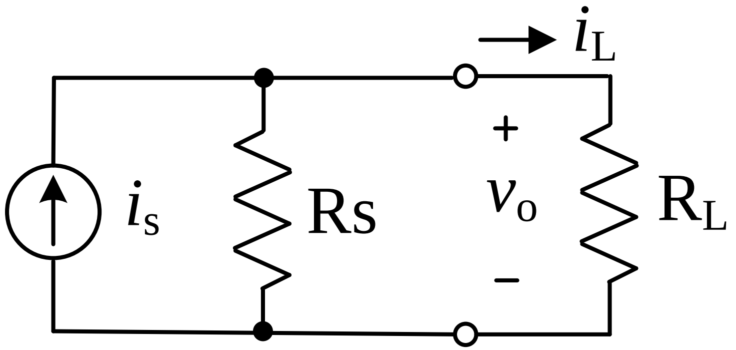


$$i_L = \frac{v_s}{R_s + R_L}$$

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

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

Current source model
(Norton form)



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

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

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

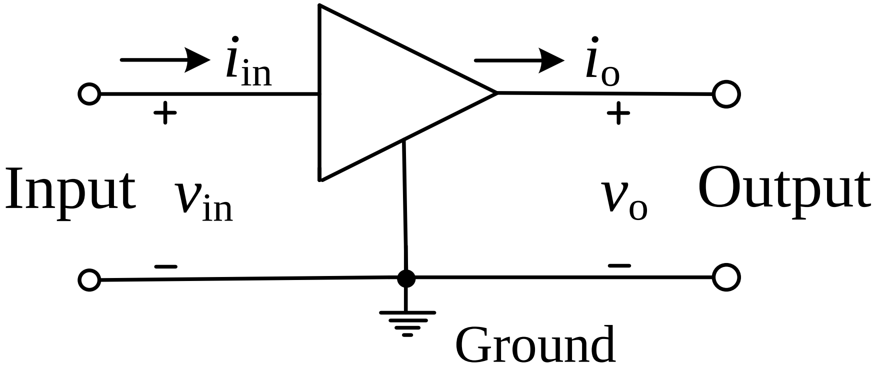
Preferred representation of a practical signal source

Voltage source (Thevenin form) if $R_s << R_L$. Ideal voltage source: $R_s = 0$.

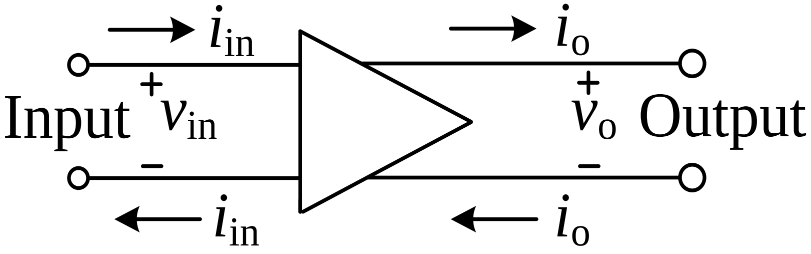
Current source (Norton form) if $R_s >> R_L$. Ideal current source: $R_s = \infty$.

2. Amplifiers

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



Amplifier with grounded input & grounded output



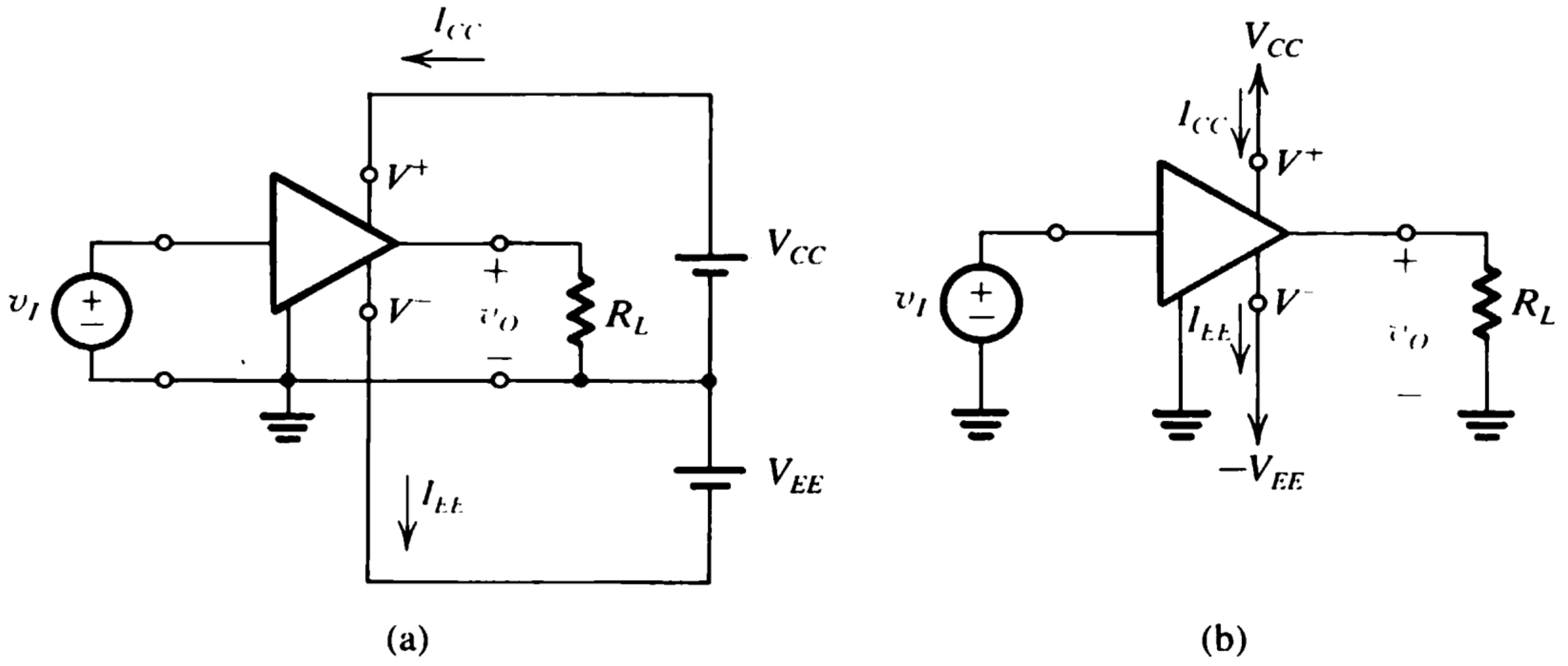
Amplifier with differential input & differential output

- 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, in general, can have multiple inputs and/or 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 that might be 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.

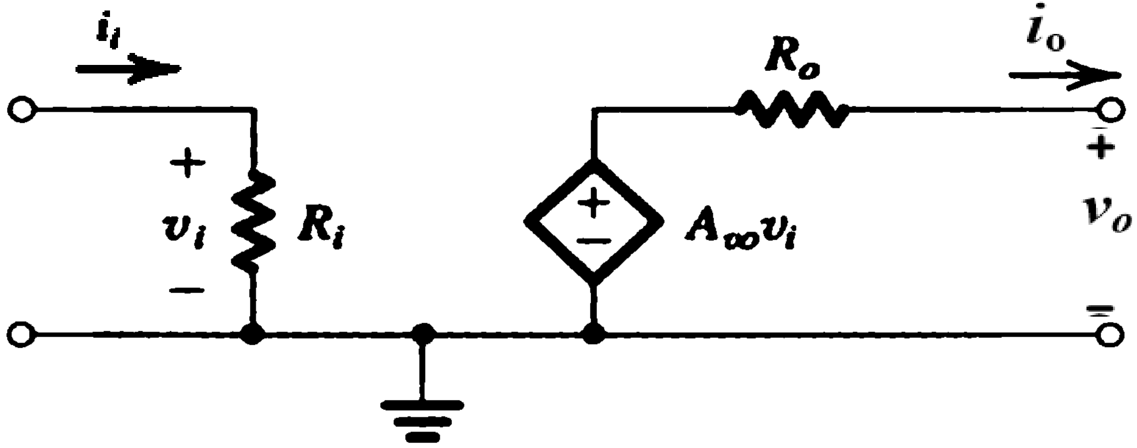


Circuit diagrams: (a) diagram with explicit connections, (b) simplified diagram, with the circuit ground as the common reference for all voltages.

Amplifier (single-ended) as 4 types of dependent sources

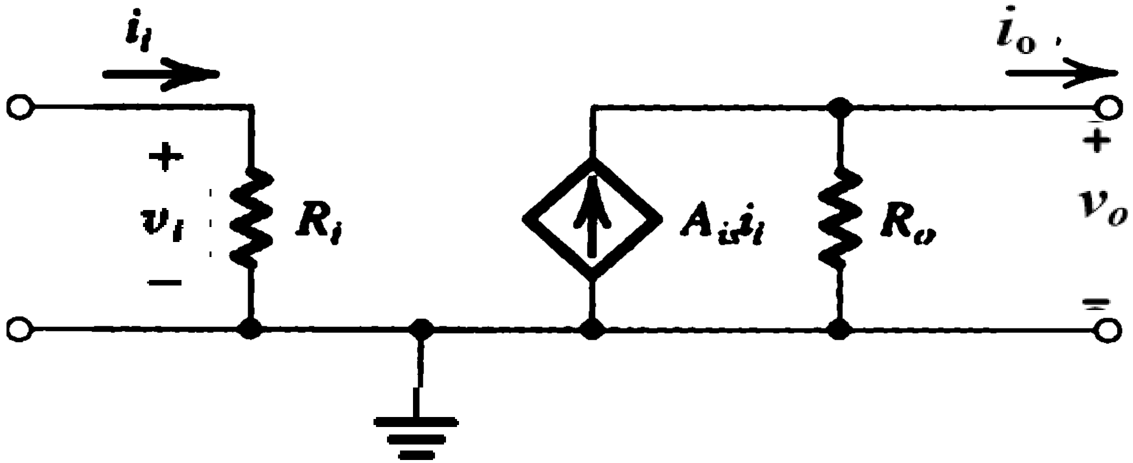
i) Voltage amplifier:
voltage-controlled voltage source (VCVS)

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

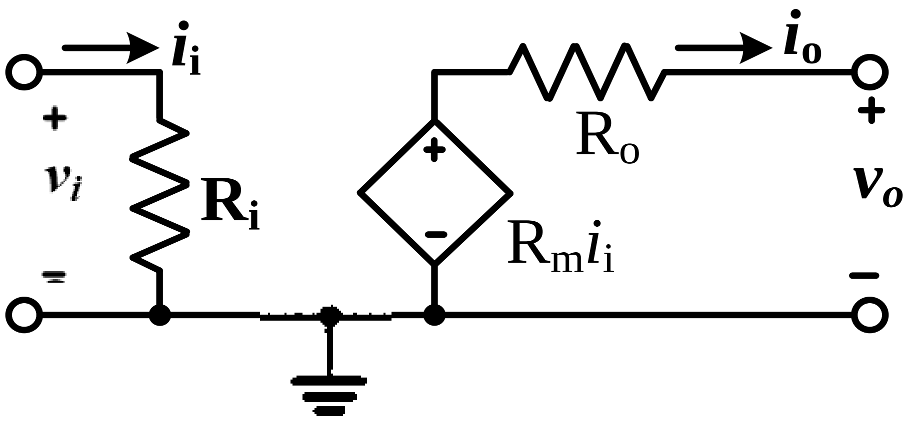


ii) Current amplifier:
current-controlled current source (CCCS)

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

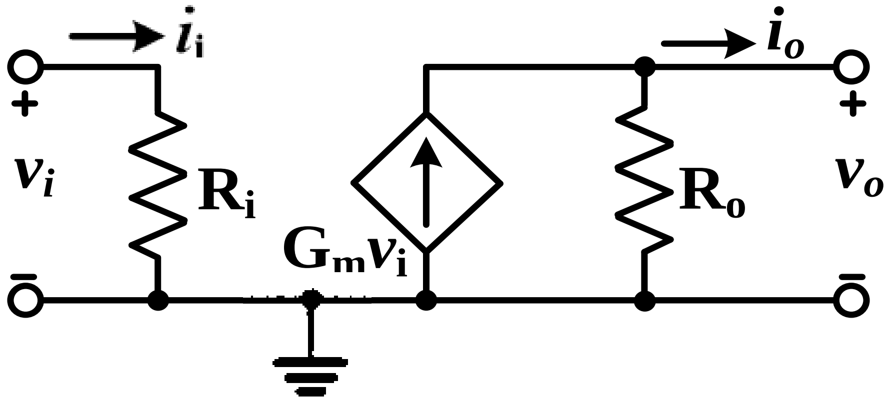


iii) Trans-resistance amplifier:
current-controlled voltage source CCVS)
Open-circuit trans-resistance: R_m
Ideal CCVS: $R_i = 0$, $R_o = 0$



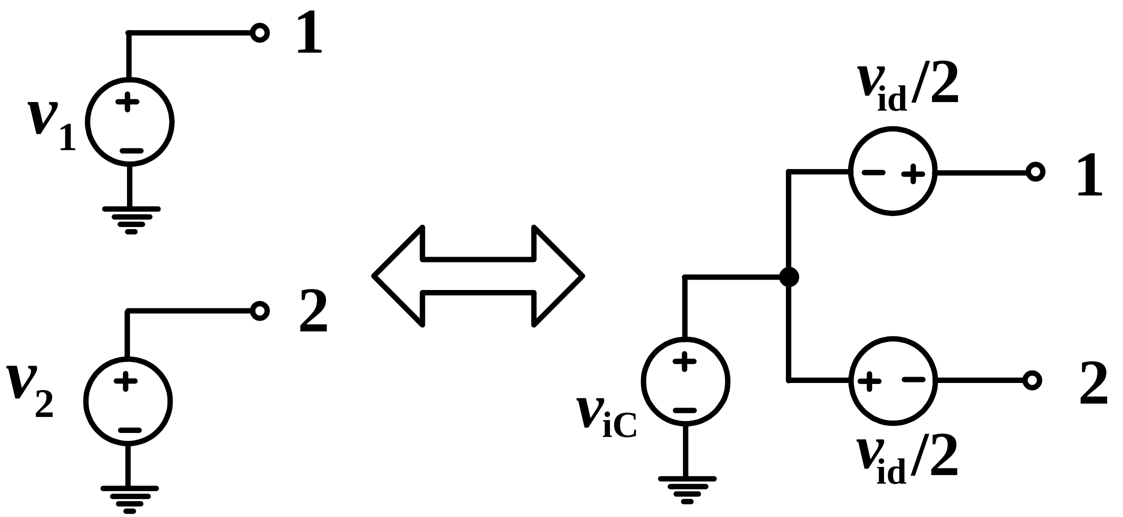
iv) Trans-conductance amplifier:
voltage-controlled current source (VCCS)

Short-circuit trans-conductance: G_m
Ideal VCCS: $R_i = \infty$, $R_o = \infty$



Differential signal

A differential signal has two voltages with Gnd as the reference. It is modeled as a common–mode (CM) voltage and a differential-mode (DM) voltage.

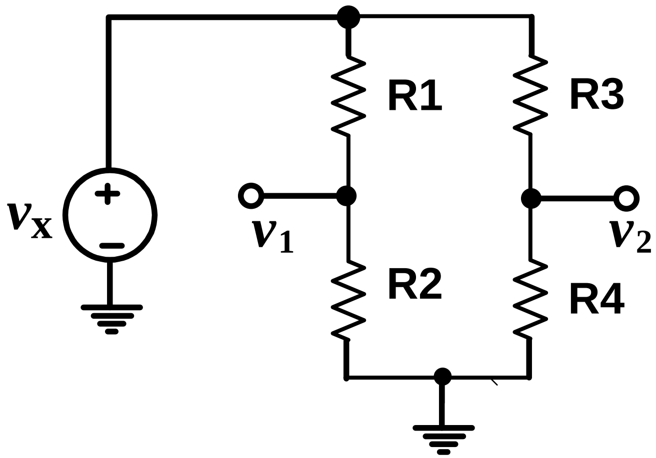


Terminal voltages: v_1 & v_2

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

Terminal voltages in terms of DM and CM voltages:
$v_1 = v_{ic} + v_{id}/2$; $v_2 = v_{ic} - v_{id}/2$

Differential signal example



Wheatstone bridge balance detection

Bridge excitation voltage: v_x. Output terminal voltages: v_1 & v_2.

$v_1 = \frac{R_2}{R_1+R_2} v_x$. $v_2 = \frac{R_4}{R_3+R_4}$. CM voltage $v_{ic} = \frac{v_1+v_2}{2}$. DM voltage $v_{id} = v_1 - v_2$.

i) Balanced bridge: Let $R_1 = R_2$ & $R_3 = R_4$ $\Rightarrow$ $v_1 = v_2 = v_x/2$.

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

ii) Unbalanced bridge: Let $R_1 = R_2$ & $R_3 = R_4(1+\delta)$ $\Rightarrow$ $v_1 = \frac{v_x}{2}$ & $v_2 = \frac{v_x}{2+\delta}$

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

$v_{id}/v_{ic} \approx \delta/2$ $\Rightarrow$ DM voltage is a small fraction of CM voltage.

To detect the imbalance, we use a differential amplifier. It takes v_1 & v_2 as the inputs, amplifies the small DM voltage, and rejects the large CM voltage.

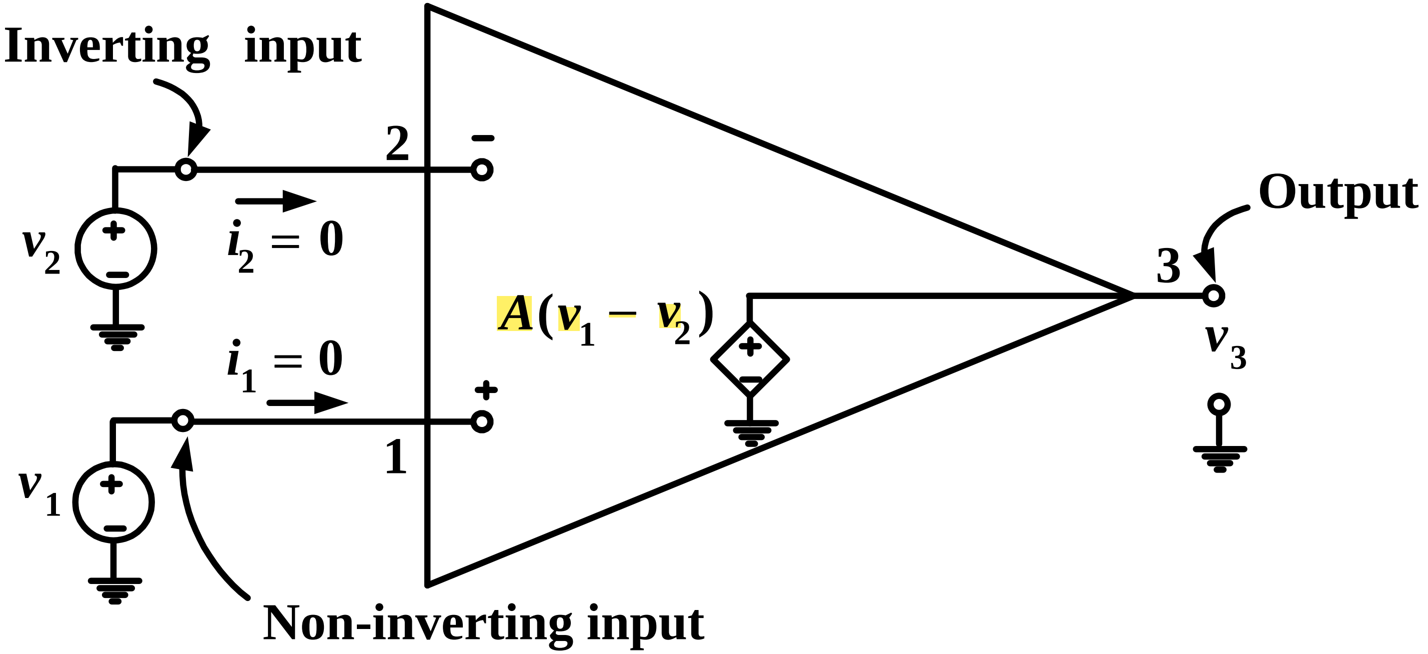
Differential amplifier

- Differential input voltage

Non-inverting input (1-Gnd): v_1
Inverting input (2-Gnd): v_2
DM input voltage: $v_{id} = v_1 - v_2$
CM input voltage: $v_{ic} = (v_1 + v_2)/2$
$v_1 = v_{\text{ic}} + v_{id}/2$
$v_2 = v_{\text{ic}} - v_{id}/2$

- Single-ended output voltage

(3-Gnd): v_3



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. Operational Amplifier

Operational amplifier (op amp)

Direct-coupled (dc) high-gain amplifier with differential voltage input & single-ended voltage output.

• Developed for mathematical operations on signal waveforms.

• Main objective: Circuit parameters decided by passive components & nearly independent of electronic device parameters.

• 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 & pins

- Two supply terminals: +ve supply & −ve supply. Labeled V_{CC} & $-V_{EE}$; V_{CC+} & V_{CC-} ; V_+ & V_- ; or V_{DD} & V_{SS}).
- The supplies are connected to the circuit ground (Gnd), implicitly (as in the left figure) or explicitly (as in the right figure). Op amp itself does not have the Gnd terminal.
- The two supply voltages may not be equal. Many applications use single-supply circuits, with one of the two supply terminals connected to Gnd.
- Minimum number of pins for single op amp: 5 pins (inputs: 2, output: 1, supplies: 2).
- Additional special-purpose pins: frequency compensation (1), offset nulling (2).
- Minimum number of pins for chip with 4 op amps (quad op amp chip): 14.

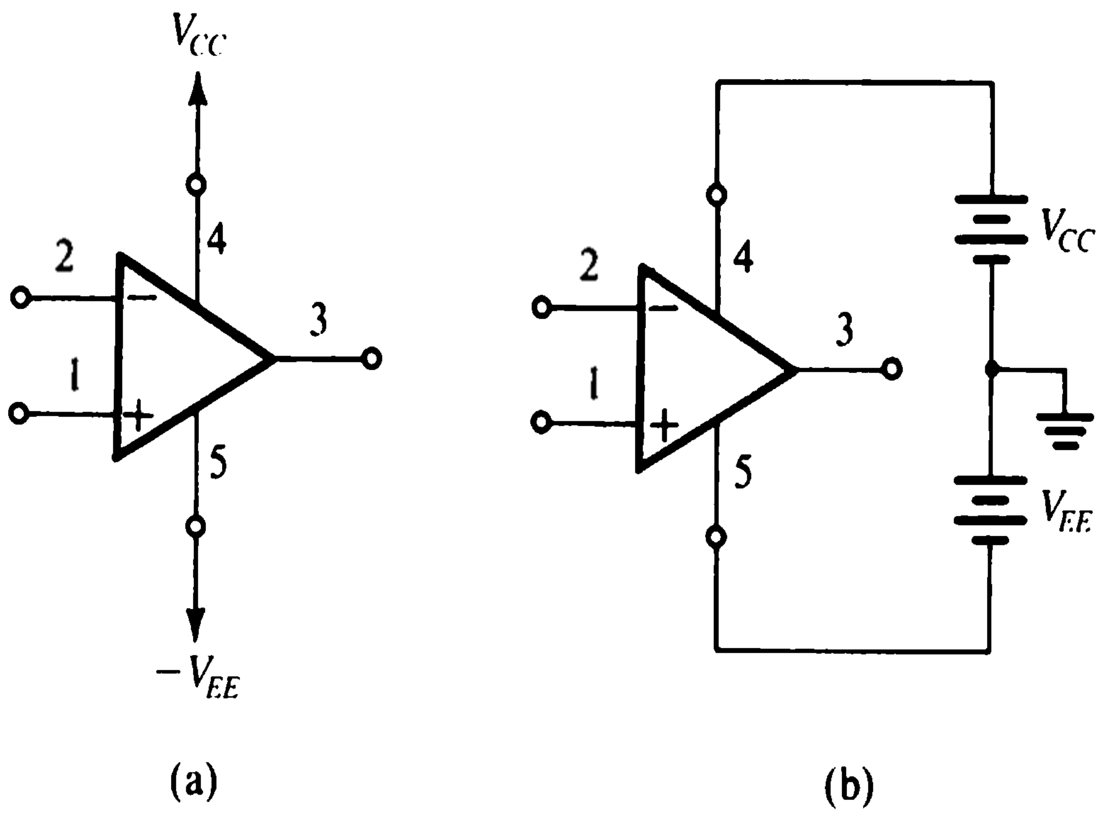
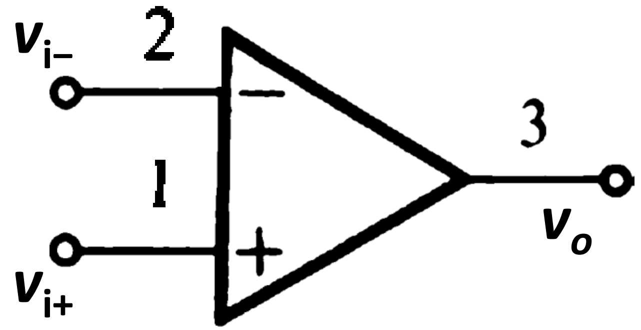


Figure 2.2 The op amp shown connected to dc power supplies.

Simplified op amp circuit symbol



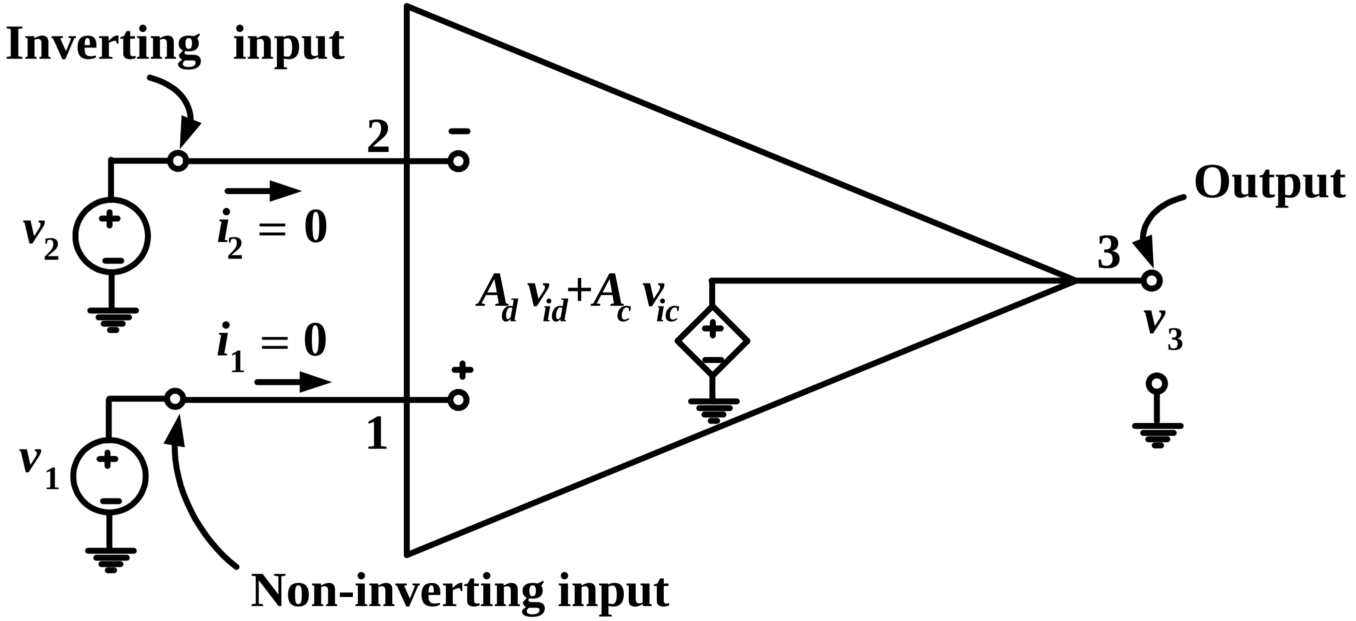
- Amplifier symbol with 3 terminals:
  - inverting input terminal (1)
  - non-inverting input terminal (2)
  - output terminal (3).

• Supply voltage terminals are not shown in the symbol. All terminal voltages are with reference to the circuit ground (Gnd), which is not shown in the symbol.

- 3 single-ended ports
  - non-inverting input port (1-Gnd): v_{i+}
  - inverting input port (2-Gnd): v_{i-}
  - output port (3-Gnd): v_o

Op amp input-output relation

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



Ideal op amp

- Infinite input resistances for the two inputs (zero input currents: $i_1 = 0$, $i_2 = 0$).
- $A_d \to \infty$ & $A_c \to 0$ $\Rightarrow v_{id} = v_3 / A_d \to 0$, for finite v_3.
- Zero voltage across the input terminals with zero input currents is known as "virtual short" across the input terminals.
- Zero output resistance (output voltage independent of the load current).

Op amp in linear operation

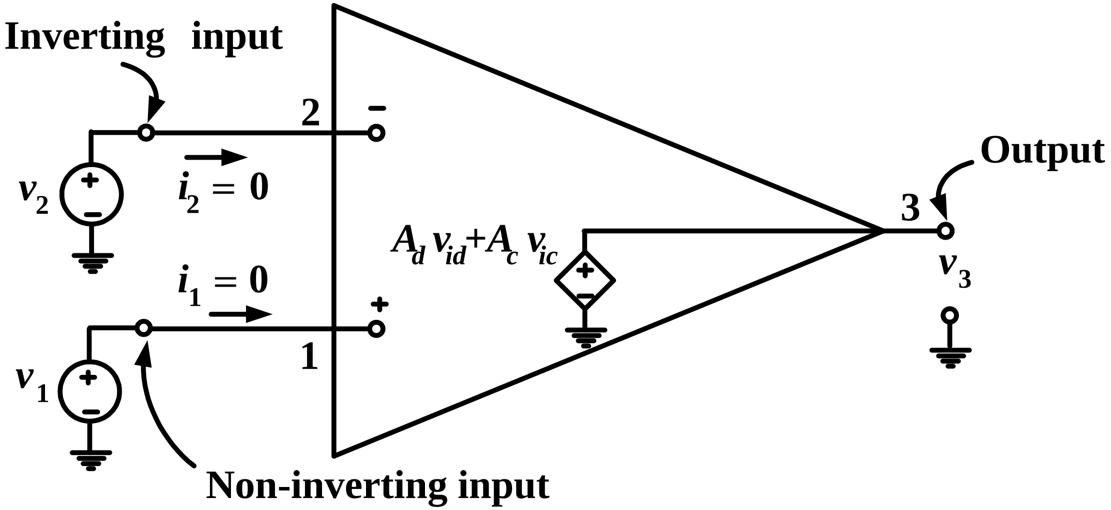
• $v_3 = A_d v_{\text{id}}$, assuming $A_c = 0$.

For finite output v_3 and $A_d \rightarrow \infty$,

DM input $v_{\text{id}} = v_3 / A_d \rightarrow 0$.

• Input resistances $R_{i1} \rightarrow \infty$, $R_{i2} \rightarrow \infty \Rightarrow i_1 = 0$, $i_2 = 0$.

• Virtual short across the input terminals (zero differential voltage, zero input currents): $v_{\text{id}} = 0$, $i_1 = 0$, $i_2 = 0$.



• Virtual short across the input terminals is very useful in analyzing op amp circuits. This assumption is applicable only during linear operation of the op amp. The conditions for it are to be satisfied by external circuit & input signals. Input currents may increase, and output may be distorted during nonlinear operation.

• Input and output voltage limits for linear operation:

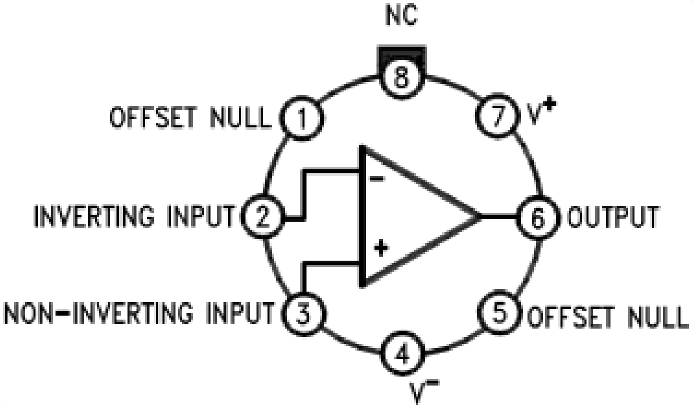
CM input: $V_{CC+} > V_{ICH} > [v_1, v_2] > V_{ICL} > V_{CC-}$.

Output: $V_{CC+} > V_{OH} > v_3 > V_{OL} > V_{CC-}$.

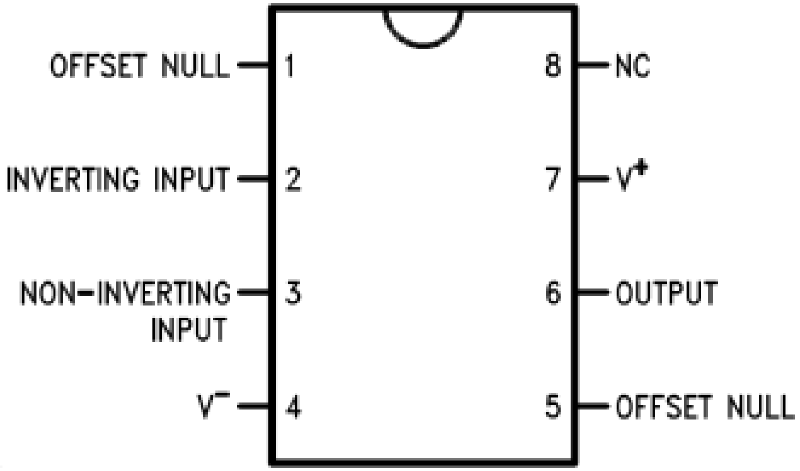
Op amp example: General-purpose op amp LM741

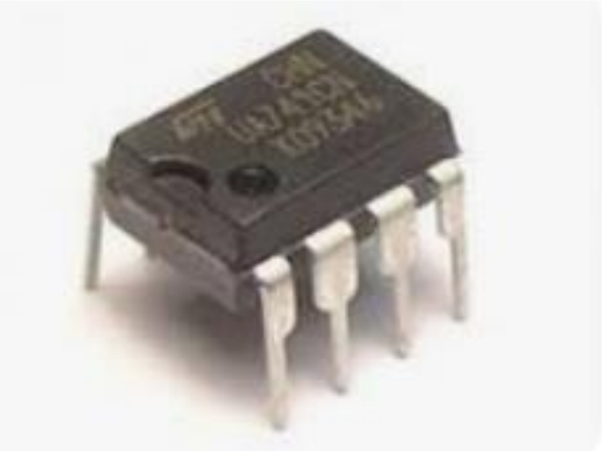
- Supply: ± 10 V to ± 18 V, ± 15 V typical
- $A_d > 50 \times 10^3$
- Input range: ± 12 V
- Output swing: ± 12 V
- Output short-circuit current: 25 mA
- Power consumption < 100 mW

LMC Package
8-Pin TO-99
Top View



NAB Package
8-Pin CDIP or PDIP
Top View

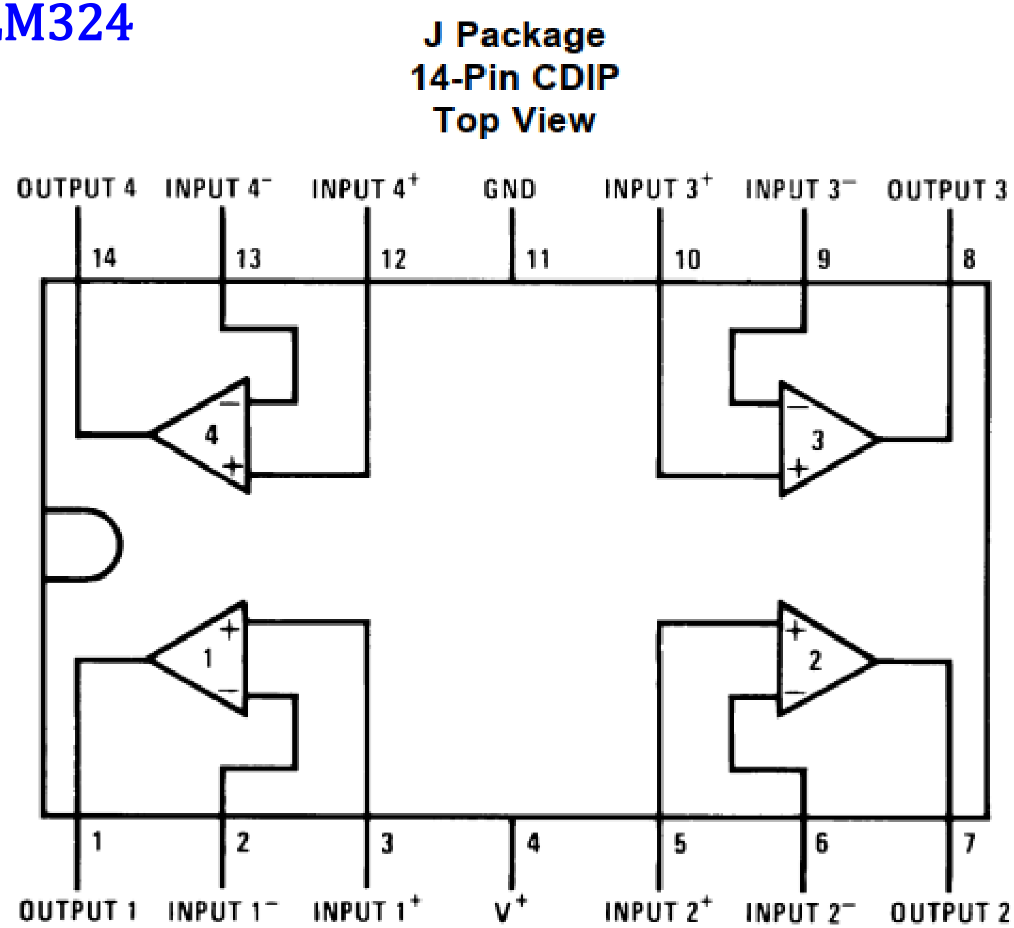


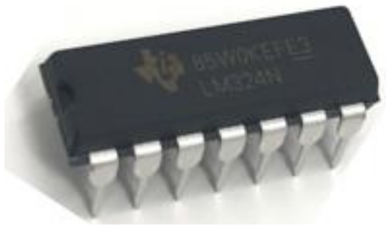


Op amp example: Low-Power Quad Operational Amplifiers LM324

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

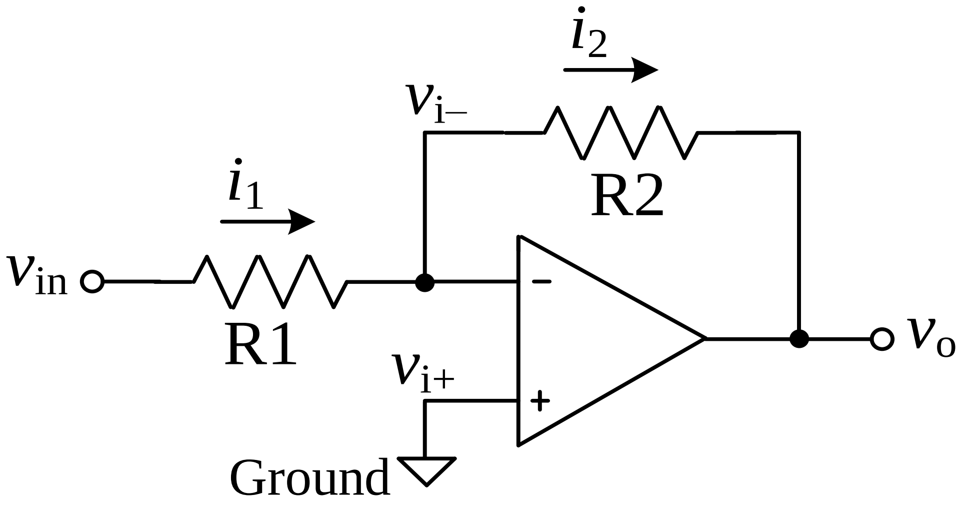
- Supply: $\pm$1.5 V to $\pm$16 V, $\pm$2.5 V typical
- $A_d > 50{\times}10^3$
- Input range: –2.5 V to 1 V
- Output swing: –2.5 V to 1 V
- Output short-circuit current: 40 mA
- Power consumption < 15 mW





4. Linear Circuits

4.1. Inverting Amplifier Circuit



$v_{i+} = 0.$

Virtual short: $v_{i-} = v_{i+} = 0.$ $i_1 = i_2.$

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

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

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

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

Current gain: $A_i = (v_o/R_L)/(v_{in}/R_1) = -R_2/R_L.$

Power gain: $A_p = A_v A_i\,.$

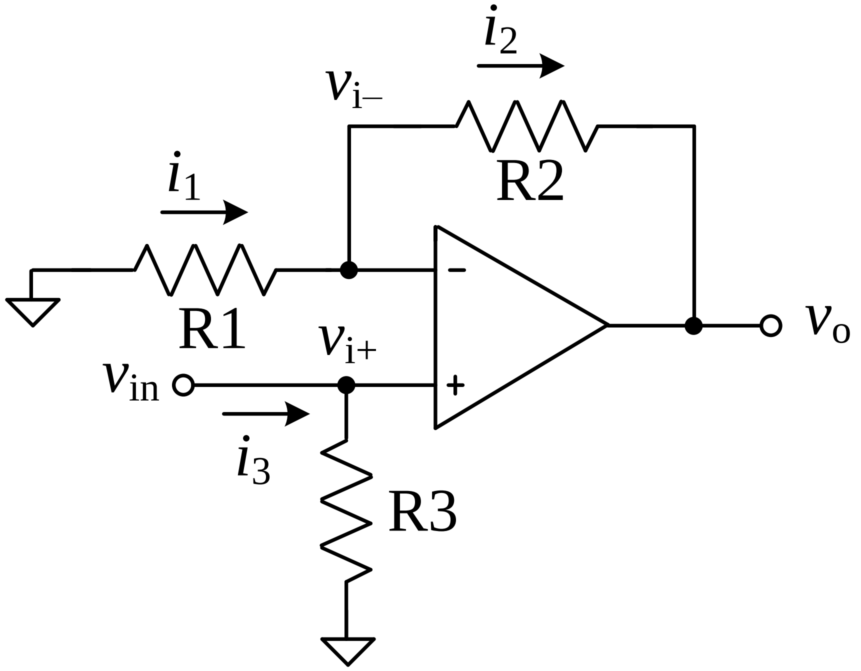
- **Circuit operation:** It is using negative feedback (visited later), which opposes disturbance. Check the operation with virtual short assumption & a disturbance at the −ve input. If v_{i-} increases, v_o decreases, i_2 increases, v_{i-} decreases, leading to virtual short restoration. If the op-amp input terminals are interchanged, an increase in v_{i+} will cause further increase leading to virtual short violation.

- Current & power gains depend on load resistance (not shown). R_{in} can be decreased, without affecting the gain, by connecting a resistor between input and ground.

- *Application:* Precise inverting gain with low to moderate R_{in}.

- *Example:* Let $R_1 = 10$ kΩ, $R_2 = 100$ kΩ. $R_L = 1$ kΩ. $A_v = -R_2/R_1 = -10.$ $R_{in} = R_1 = 10$ kΩ .

4.2. Noninverting Amplifier Circuit



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

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

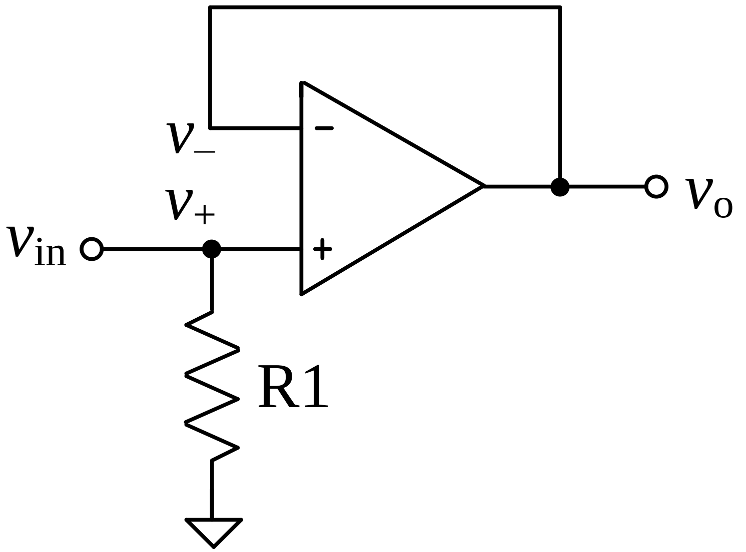
R3 is optional & can be selected for the desired R_{in}.

Basis for circuit operation: Negative feedback. Check the circuit operation, with virtual short assumption & a disturbance at the −ve input. If v_{i-} increases, v_o decreases, i_2 increases, v_{i-} decreases, leading to virtual short restoration. Next check with the op-amp input terminals interchanged.

Application: Precise noninverting gain with high, moderate, or low R_{in}.

Example: Let $R_1 = 10$ kΩ, $R_2 = 100$ kΩ, $R_3 = 1$ MΩ. $A_v = 1 + R_2/R_1 = 11$, $R_{in} = R_3 = 1$ MΩ.

4.3. Non-inverting Unity Follower Circuit (Unity Buffer)



It is a special case of noninverting amplifier with unity voltage gain.

Voltage gain: $A_v = 1$
Input resistance: $R_{in} = R_1$

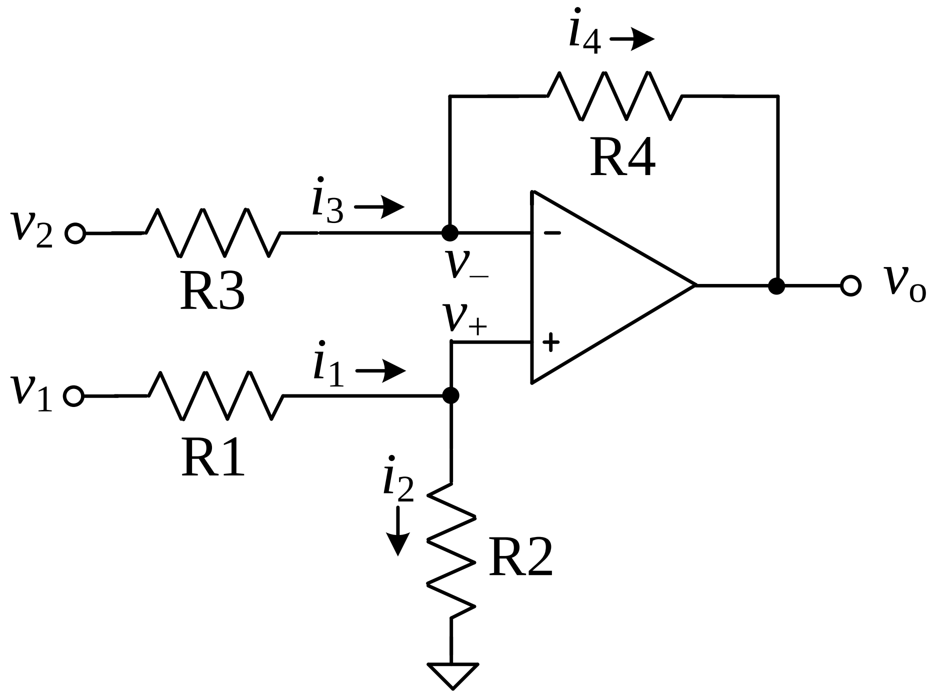
Application: Buffer amplifier with very high R_{in} and very low R_o. It is used for connecting a source with high source resistance to a relatively low value load resistance without causing voltage attenuation. It provides unity voltage gain and large current gain.

4.4. Difference Amplifier Circuit

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

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

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



$$v_o = v_1[R_2/(R_1+R_2)]\,(1+R_4/R_3) - v_2\,(R_4/R_3)$$

$$= v_1[\alpha/(1+\alpha)](1+\alpha) - v_2\alpha = \alpha\,(v_1 - v_2)$$

DM gain $A_d = \alpha$.

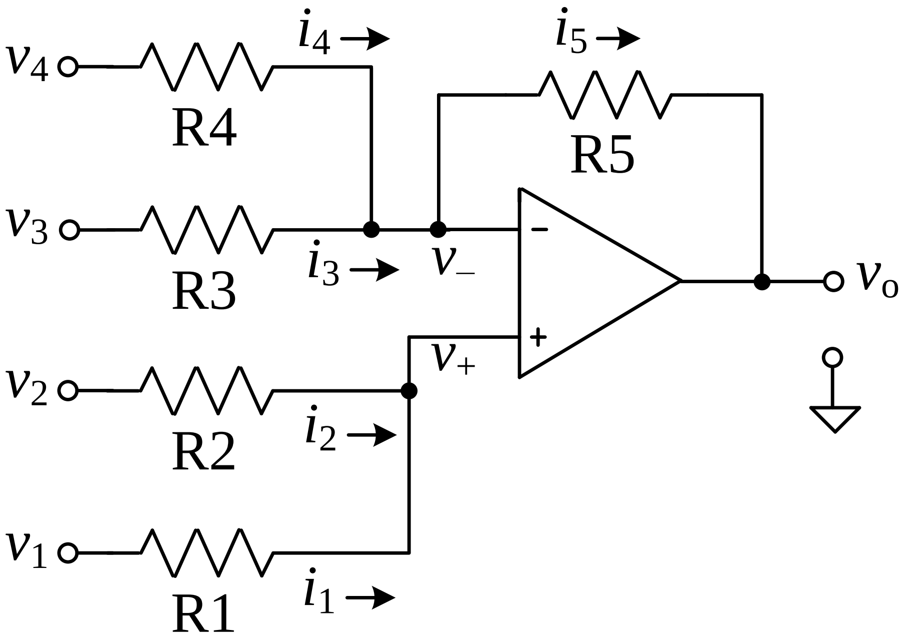
CM gain $A_c = 0$

$R_{in1} = R_1 + R_2$, $R_{in2} = R_3$.

- 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.

$$v_o = \alpha\,(v_1 - v_2) + v_3[1/(1+\alpha)]\,/(1+\alpha)] = \alpha\,(v_1 - v_2) + v_3$$

4.5 Summing & Difference Amplifier



Virtual short assumption

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

For finding voltage gain & input resistance for each input, set other inputs as 0.

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

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

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

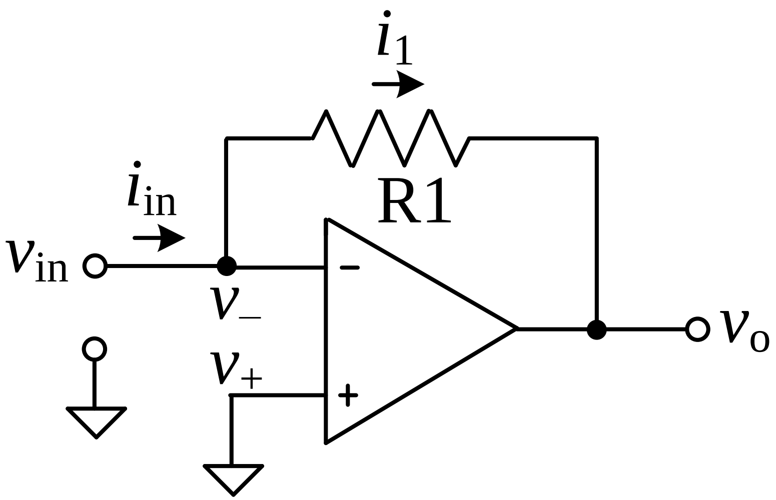
$R_{in1} = R_1 + R_2, \qquad R_{in2} = R_1 + R_2,$

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

- 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.
- Mostly used as multi-input inverting summer or two-input difference amplifiers.

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

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

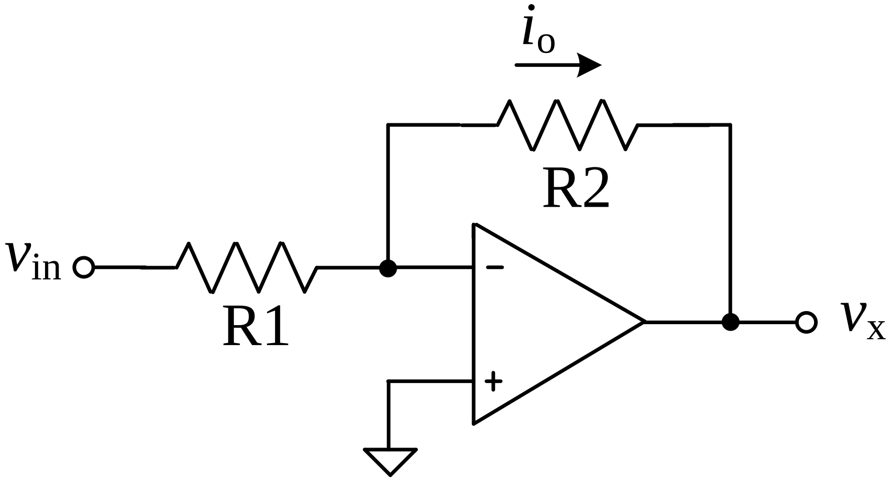


$v_O = v_{i+} - R_1 i_{in} = -R_1 i_{in}$

$R_{in} = 0$

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

4.7. Voltage-to-Current (V/I) Converter (Transconductance Amplifier)

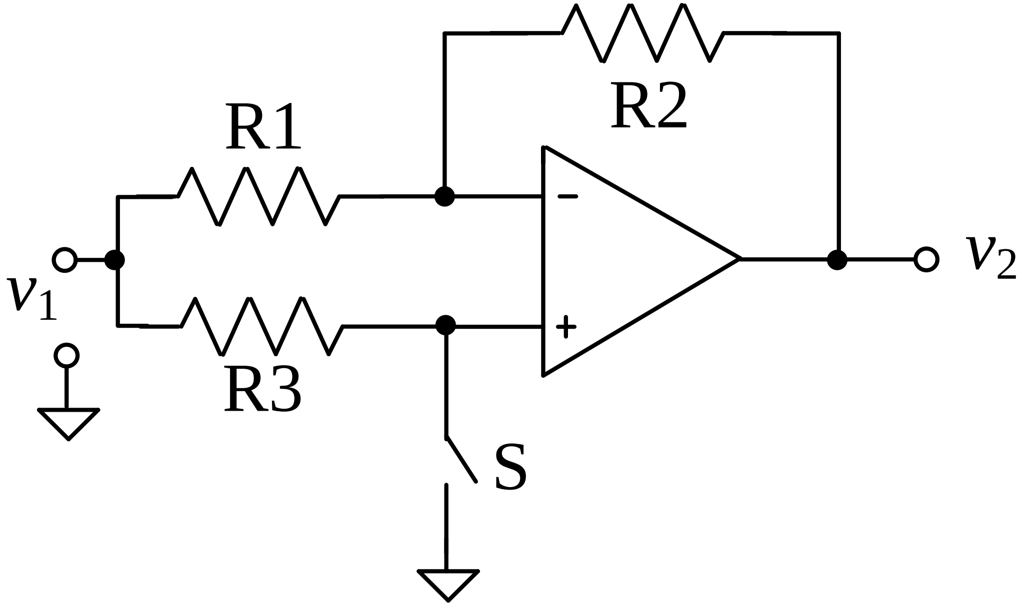


Re-purposed inverting amplifier circuit, for output current in load R2.

$\boldsymbol{i_O = v_{in}/R_1}$
$\boldsymbol{R_{in} = R_1}$
$\boldsymbol{v_X = -R_2\, i_O}$

- **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 needed for grounded load (load ewith 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.**

4.8. Polarity-Controlled Amplifier



S: electronically-controlled switch.

Let $R_1 = R_2$

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

$\Rightarrow A = -1$

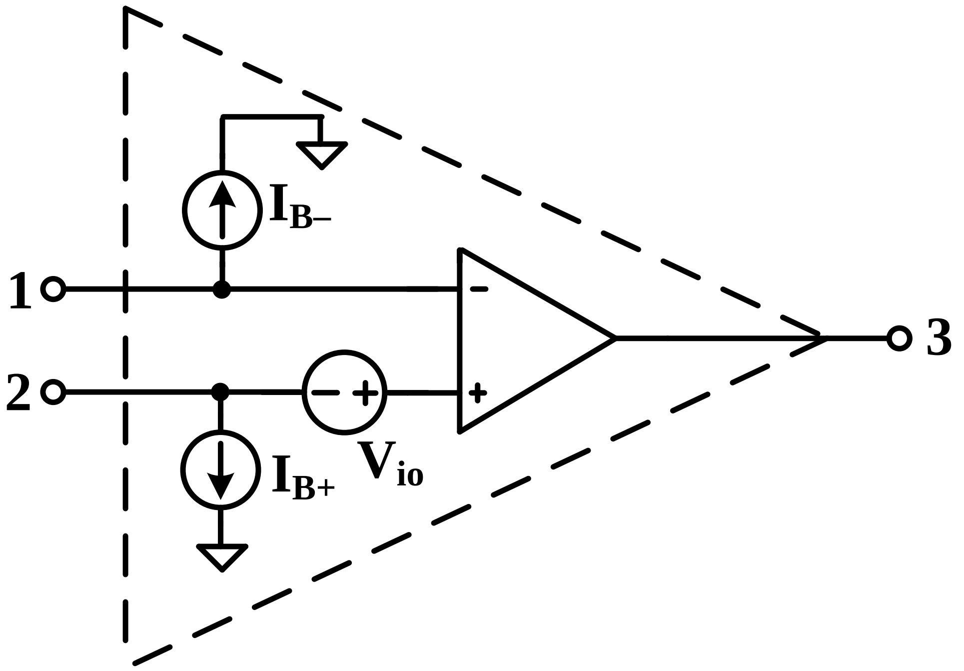
S open: $v_2 = (-R_2/R_1)\ v_1 + (1+R_2/R_1)\ v_1 = v_1$

$\Rightarrow A = +1$

The circuit gain is set as +1 and −1 using the electronically controlled switch S. It is a simple example of 'programmable' or 'digitally-controlled' analog circuit.

4.9. Practical Op Amp

• Op-amp linear operation has limits for CM input voltage, output voltage, & output current (due to DC supplies & internal circuit)



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.

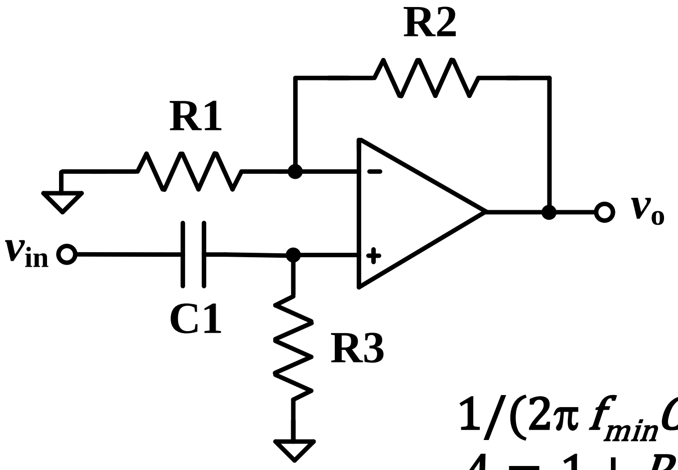
• Finite input & output resistances.

• Finite diff. 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).

4.10. AC Amplifier Circuits

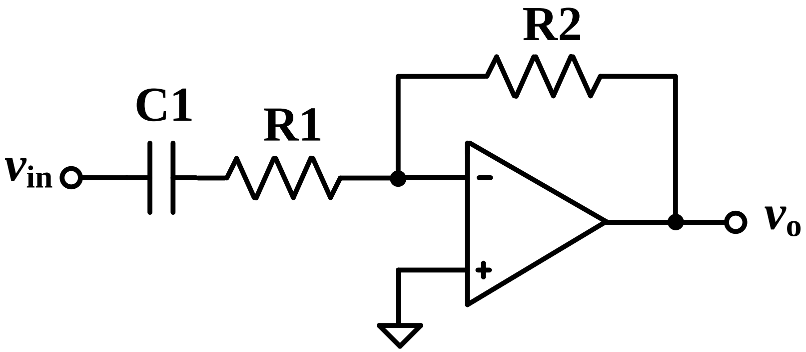
Amplification of a small time-varying (AC) component superimposed on a large constant (DC) component. A capacitor is connected in series with the input to block the DC component & couple the AC component. Capacitor impedance at the lowest frequency (f_{min}) << input resistance R_{in} & the circuit must have a DC current path from each op-amp input terminal to Gnd.

Noninverting 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



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

5. Feedback Amplifier & Oscillator

- *Feedback:* Addition of a fraction of the output to the input for desirable system behavior.

- *Negative feedback: Used in amplifiers to*

- Desensitize the gain, making it less sensitive to the circuit component parameters.
- Extend the bandwidth.
- Reduce nonlinear distortion.
- Reduce noise effects.
- Control the input and output resistances: raise or lower R_{in} and R_o by appropriate feedback topology.

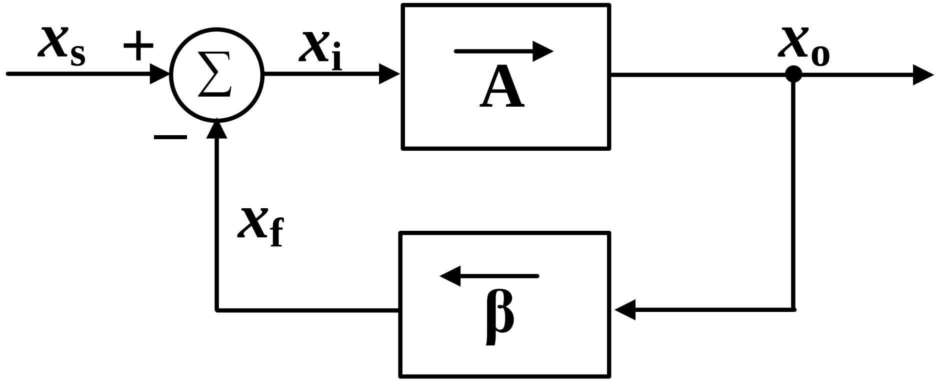
The desirable properties are obtained at the expense of gain reduction.

- *Positive feedback:* Used to realize oscillators (function generators) & bistable circuits.

- *Negative & positive feedback combination:* Used in filters (circuits with specific frequency response) for signal processing.

Feedback Amplifier

• Signal-flow diagram: input x_s, output x_o (quantities may be voltage or current).



• Blocks: 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).

$x_f = \beta\, x_o$. $\quad x_i = x_s - x_f$.

$x_o = Ax_i = A(x_s - \beta\, x_o) \;\Rightarrow\; x_o(1 + A\beta) = Ax_s$.

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

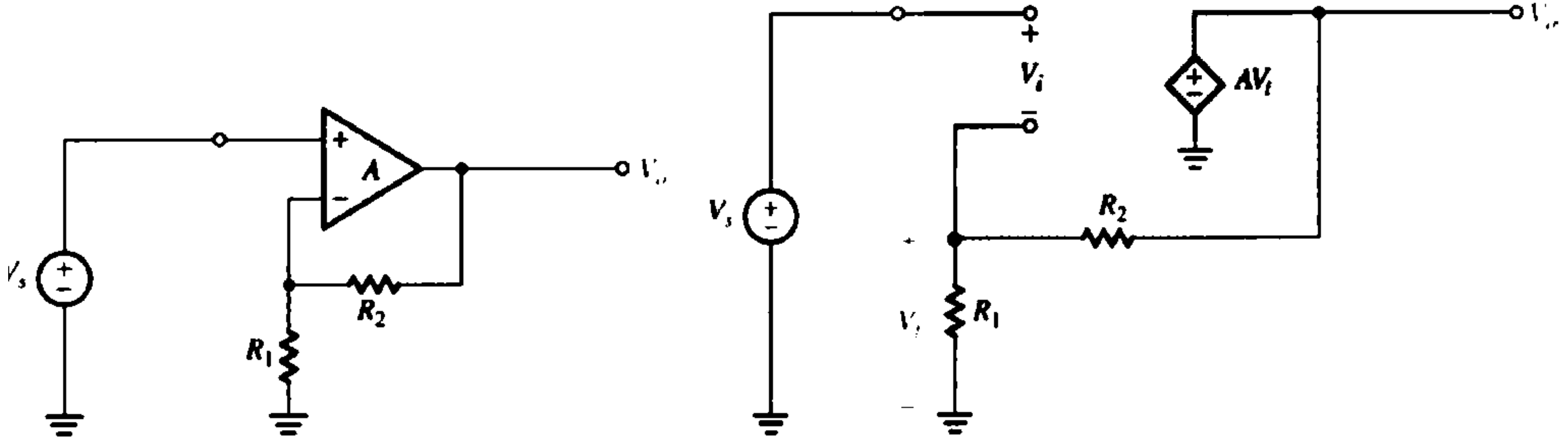
Example: $A = 10^3$ to 10^5 & $\beta = 1/10$.

(i) $A = 10^3 \Rightarrow A_f = 10/(1+10^{-2}) = 9.900$. (ii) $A = 10^5 \Rightarrow A_f = 10/(1+10^{-4}) = 9.9990$

• A (open-loop gain) may have large variability due to electronic device parameters. β depends on passive components & can be precise. A_f is precise for $A\beta >> 1$ despite variability in A.

• Negative feedback is used to obtain precise gain, but the gain is significantly reduced.

Non-inverting Amplifier as a Negative Feedback Amplifier (circuit & feedback model)



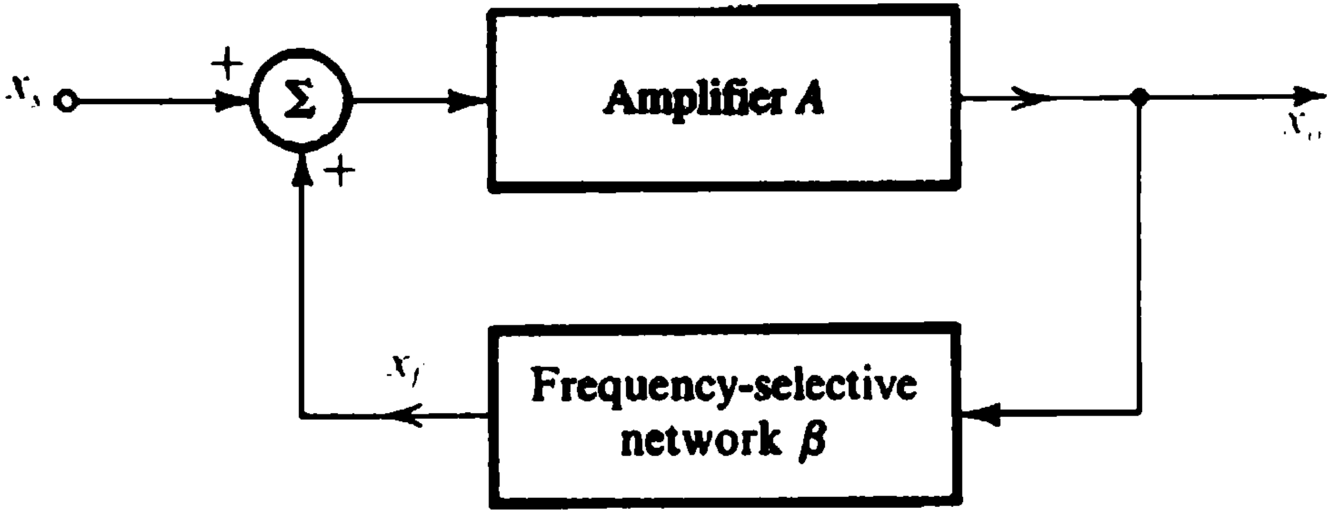
- Open-loop gain = op-amp differential gain. Feedback factor is set by resistive attenuator (R1, R2). Feedback subtraction is at the op-amp differential input.

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

- Closed-loop gain is precise if it is much smaller than the open-loop gain. 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.

Sinusoidal Oscillator

Blocks: Amplifier, +ve feedback, frequency-selective network.



Closed-loop gain

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

$A\beta = 1 \quad \Rightarrow \; A_f = \infty \;\; \Rightarrow$ Finite output for zero input.

• Sustained sinusoidal oscillation if the loop–gain is 1 at a single frequency and less than 1 at other frequencies.

•*Condition for oscillation:* Loop–gain phase should be zero, and loop–gain magnitude should be unity. Known as "Barkhausen criterion".

• Frequency-selective network for satisfying Barkhausen criterion at a single frequency. Oscillation starts due to presence of noise or power-on impulse. Output level is decided by amplifier nonlinearity (present in the circuit or designed).

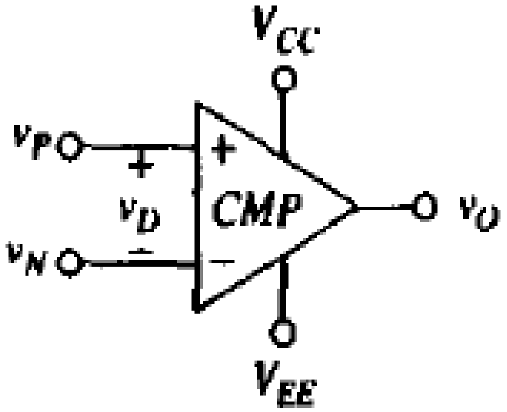
6. Nonlinear Circuits

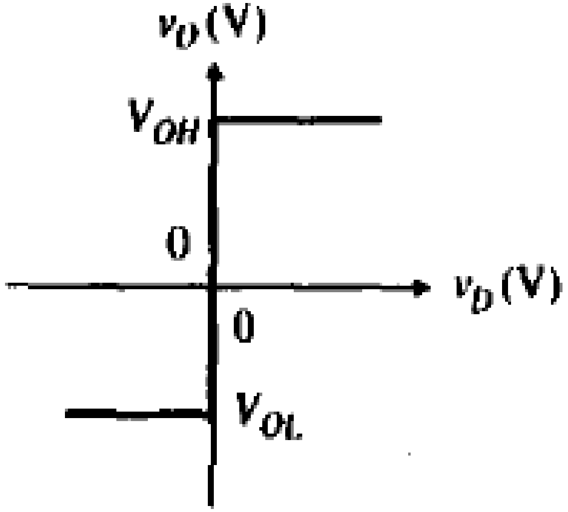
Voltage Comparator

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

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

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





• Circuit symbol: same as op amp, with analog inputs, binary output. Transfer characteristic: Very high gain at $v_p = v_n$ with sharp transition between the two output levels.

• Input swing and output levels generally dependent on V_{CC+} and V_{EE-}.

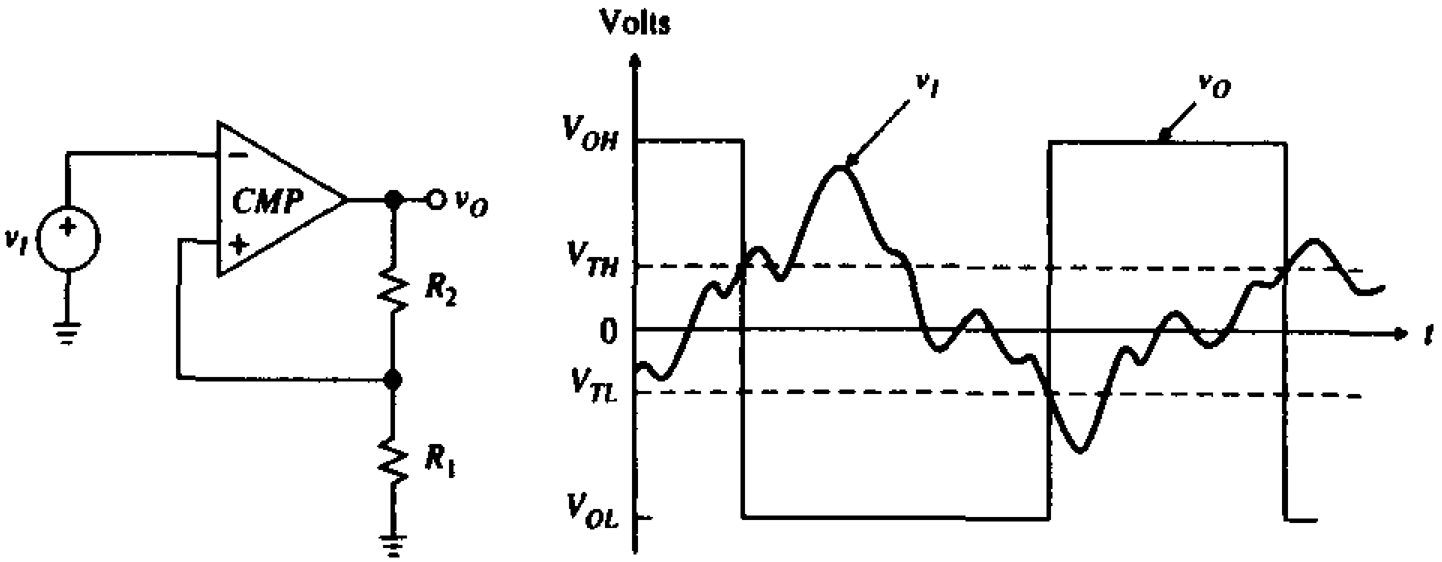
• A comparator is designed for very low input currents despite large differential input voltage. It has buffers at each input before the differential high-gain. An op amp can also be used as a comparator with due consideration for finite differential input voltage.

Schmitt Trigger

Comparator with hysteresis: high-gain differential amplifier with +ve feedback. Bistable circuit.

• Inverting Schmitt trigger: clockwise hysteresis.

• Non-inverting Schmitt trigger: counterclockwise hysteresis.



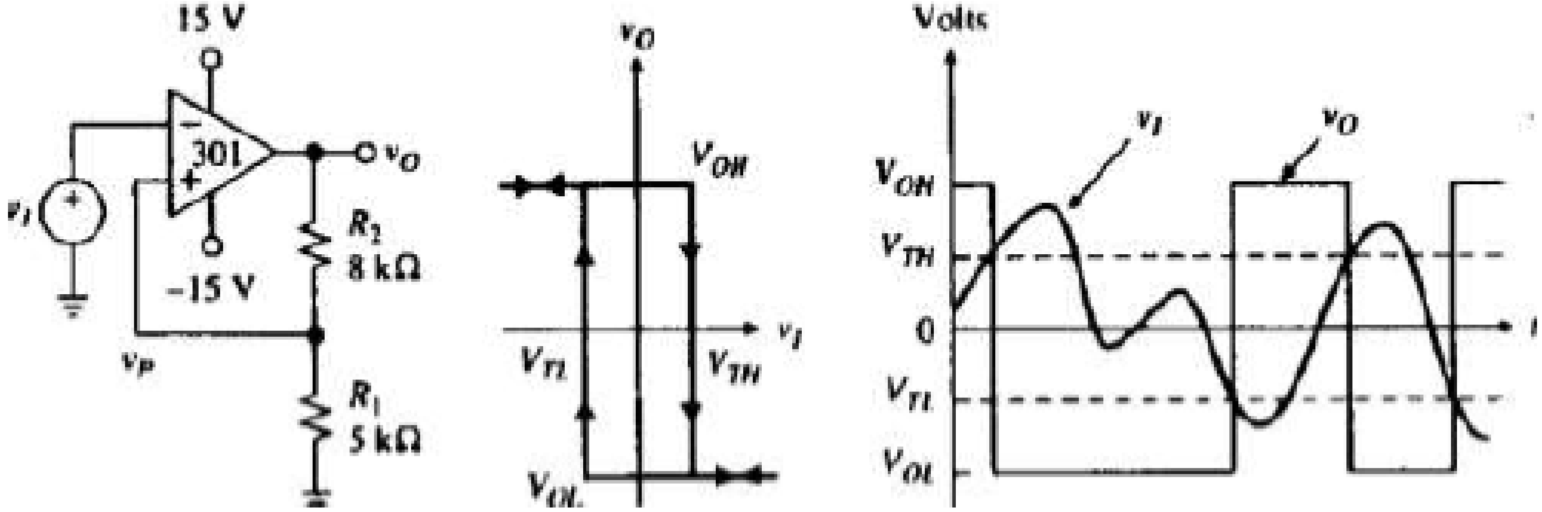
Applications: **Chatter elimination, waveform generation, signal processing.**

Inverting Schmitt trigger

$$V_{TH} = \frac{R_1}{R_1 + R_2} V_{OH}$$

$$V_{TL} = \frac{R_1}{R_1 + R_2} V_{OL}$$

$$\Delta V_T = \frac{R_1}{R_1 + R_2}(V_{OH} - V_{OL})$$

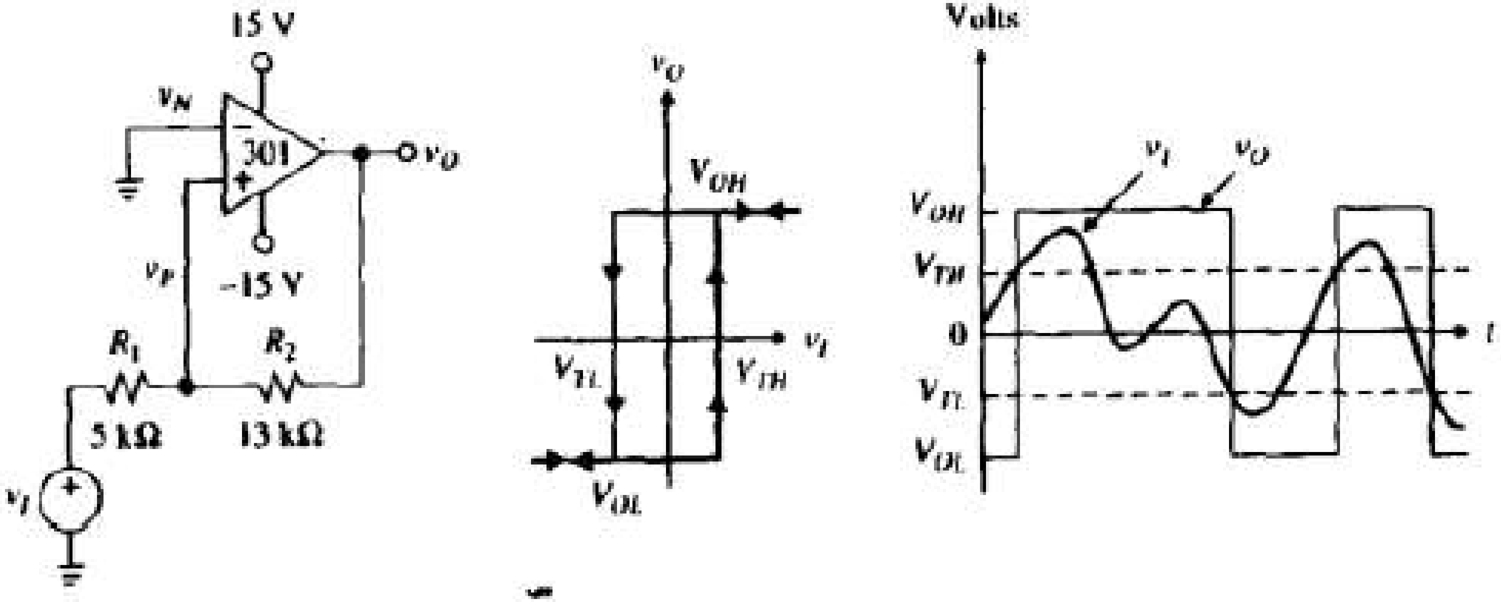


Noninverting Schmitt trigger

$$V_{TH} = -\frac{R_1}{R_2} V_{OL}$$

$$V_{TL} = -\frac{R_1}{R_2} V_{OH}$$

$$\Delta V_T = \frac{R_1}{R_2}(V_{OH} - V_{OL})$$



Thanks.