Academic Year: 2022-2023, Semester: II

Course: MS 101
EE Lectures 06 & 07

Operational Amplifier Circuits

1. Signal basics, 2. Amplifiers, 3. Op amp, 4. Linear circuits, 5. Feedback amplifier & oscillator, 6. Nonlinear circuits (comparator, Schmitt trigger)

Reference: A. S. Sedra, K. C. Smith, T. C. Carusone, &V. Gaudet, Microelectronic Circuits, 8th ed., Oxford University Press, 2020. Chs. 1, 2, 11, 13,15.

Instructors: Prem C Pandey, Joseph John, Dinesh K Sharma, and Kushal R 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.**

Noise: **Disturbance unrelated to the signal.**

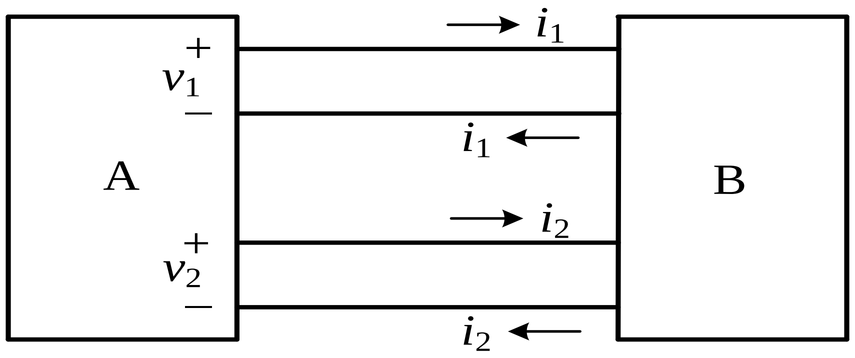
Distortion: **Disturbance related to the signal.**

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

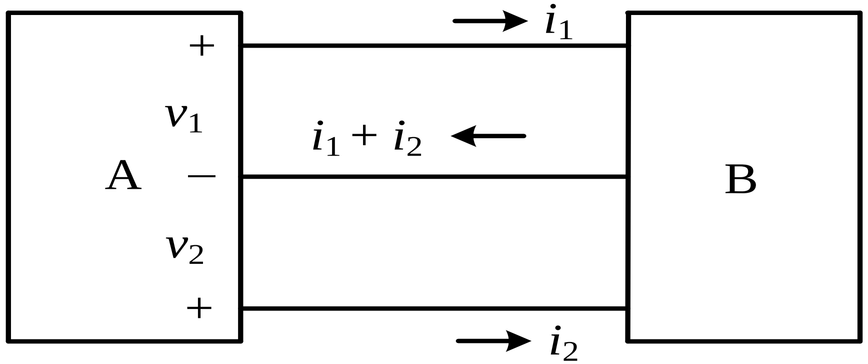
Differential signals: **Each signal needs two conductors.**

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



Two diff. signals (each with two conductors)

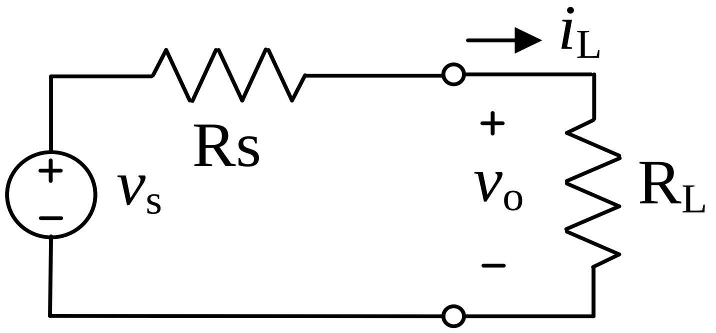


Two single-ended signals (common reference & return)

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

Two signal representations

Voltage source model
(Thevenin form)

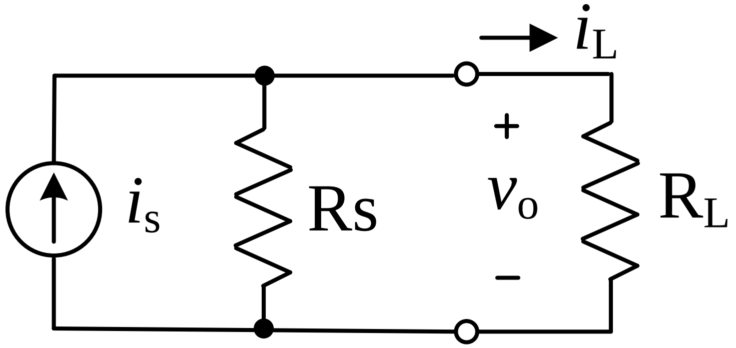


$$i_L = \frac{v_s}{R_s + R_L}$$

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

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

Current source model
(Norton form)



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

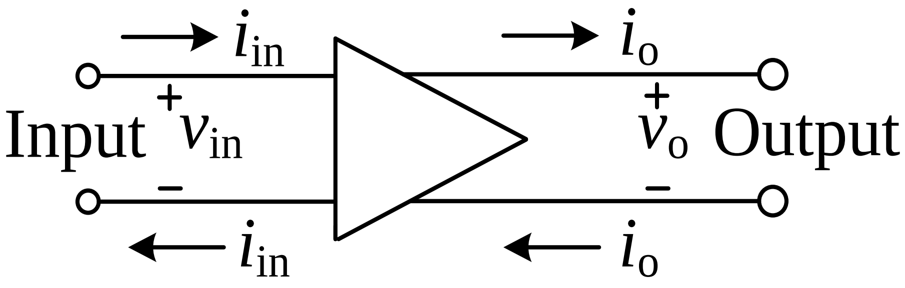
$$i_L = \frac{v_o}{R_L} = i_s \left(\frac{R_s}{R_s + R_L} \right)$$

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

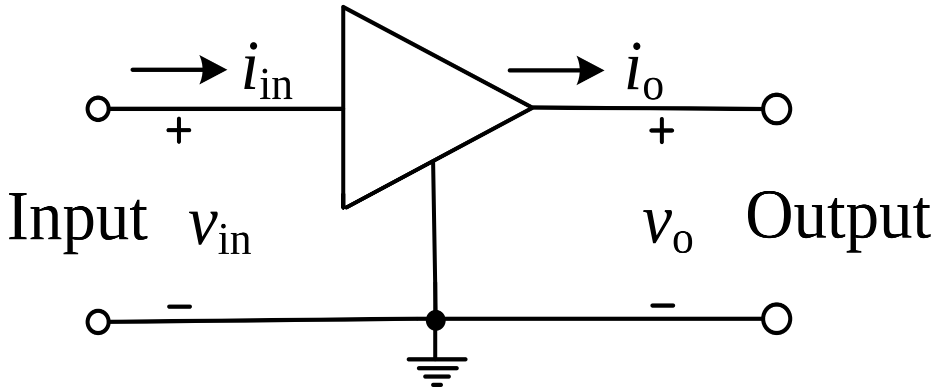
Preferred representation
$R_s << R_L$: voltage source. **$R_s >> R_L$: current source.**

2. Amplifiers

Amplifier: **Two-port circuit or device for increasing the power of the input signal, by using the power from dc source(s).**



Amplifier with diff. input & diff output



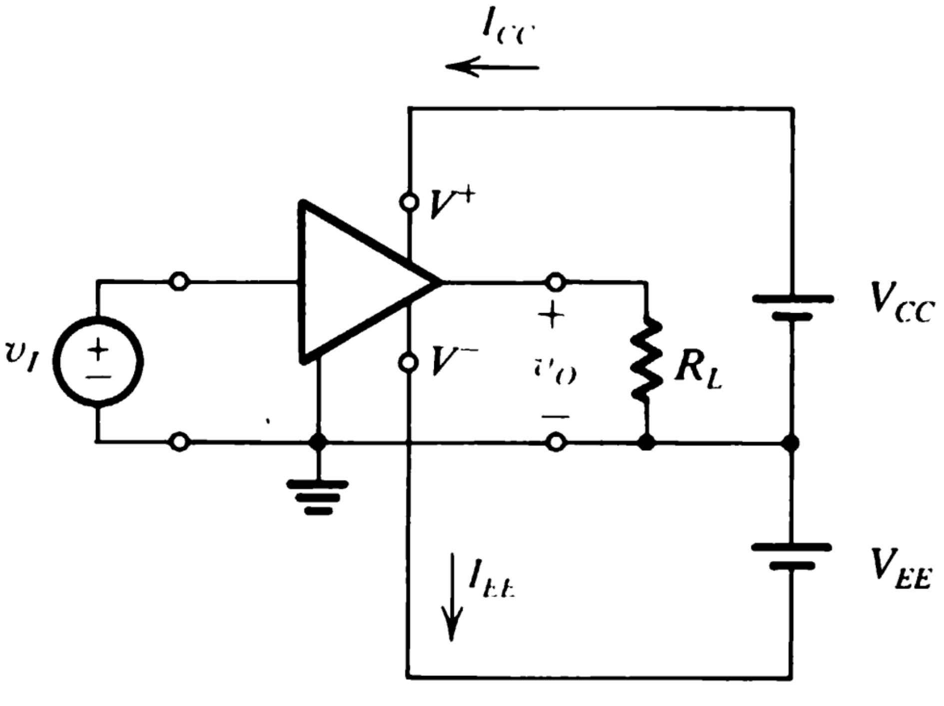
Amplifier with grounded input & grounded output

- **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: $A_p < 1$**

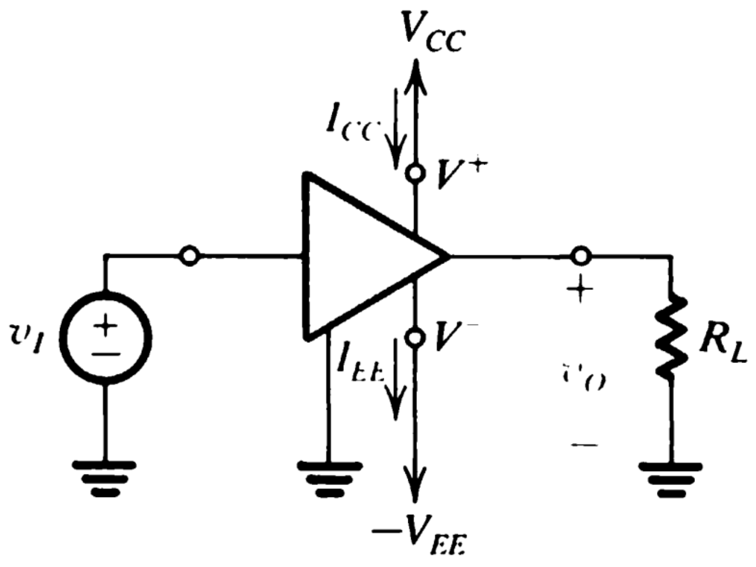
Amplifier power supplies: **Amplifier delivers more power to the output load than it draws from the input source & needs dc power sources for its operation. These dc sources supply the extra power delivered to the load as well as any power that might be dissipated as heat in the internal circuit.**

Dual supply amplifier
+ve & −ve dc sources connected to the circuit ground. Supplies need not be equal

DC power consumption
$P_{dc} = V_{CC}I_{CC} + V_{EE}I_{EE}$



(a)

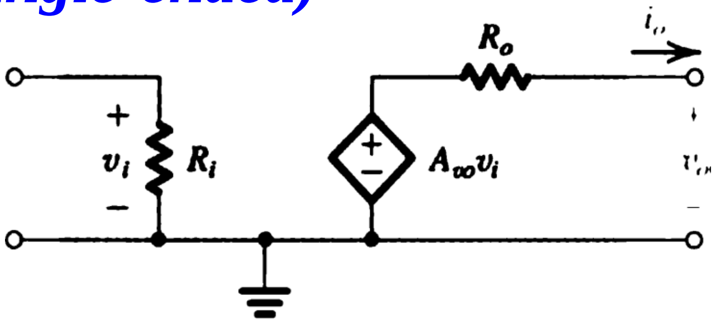


(b)

Input & output signal swings are limited by supply voltages & circuit.

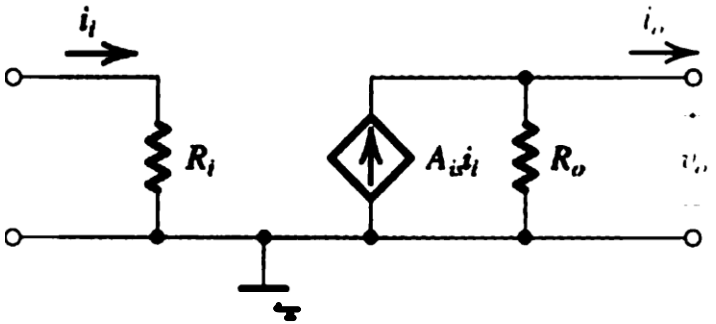
Amplifier types (single-ended)

Voltage amplifier



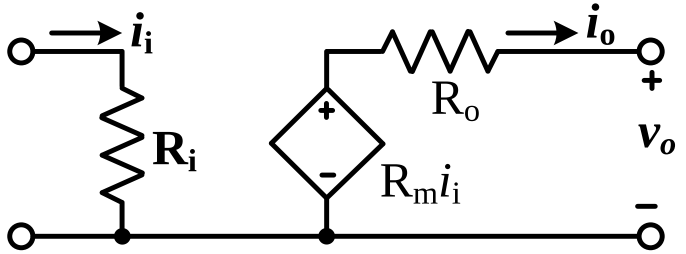
Open-circuit voltage gain A_{vo}
Ideal: $R_i = \infty$, $R_o = 0$

Current amplifier



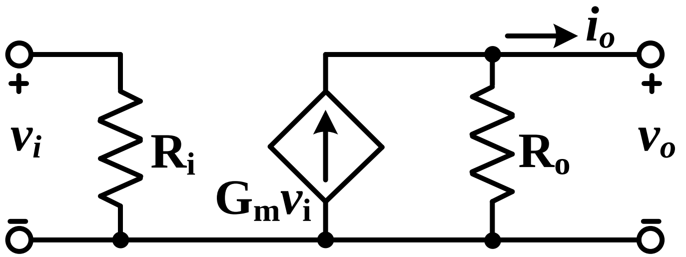
Short-circuit current gain A_{is}
Ideal: $R_i = 0$, $R_o = \infty$

Trans-conductance amplifier



Short-circuit transconductance G_m
Ideal: $R_i = \infty$, $R_o = \infty$

Trans-resistance amplifier



Open-circuit transresistance R_m
Ideal: $R_i = 0$, $R_o = 0$

Differential amplifier

Differential mode (DM) input

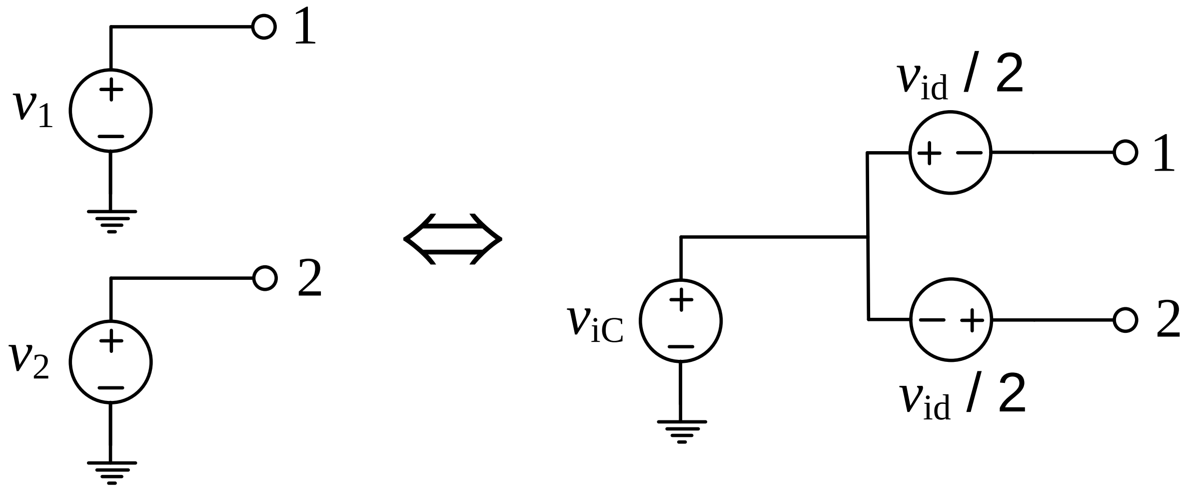
$v_{id} = v_2 - v_1$

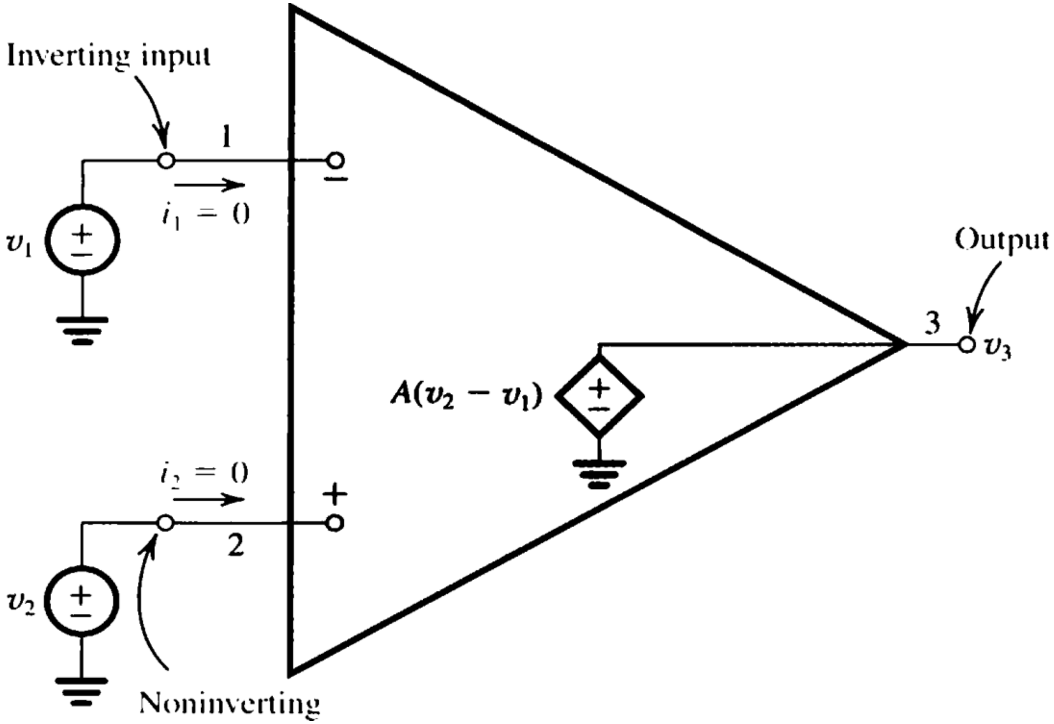
Common mode (CM) input

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

Inputs in terms of DM and CM

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





Differential voltage input & single-ended voltage output amplifier

$v_3 = A\, v_{id}$

3. Operational Amplifier

Operational amplifier (op amp)

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

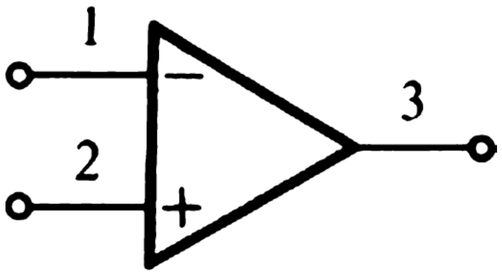
• Developed for mathematical operations on signal waveforms. It is an electronic circuit with several internal passive & active devices, available as a single-chip device, several op amps on a single chip, or op amps with other circuits on the same chip.

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

Op amp circuit symbol (simplified representation)

• Input terminals: 1, 2. Output terminal: 3.

• 3 single-ended ports with the circuit ground (not shown in the symbol) as the common terminal: 2-Gnd (v_{i+}), 1-Gnd (v_{i-}), & 3-Gnd (v_o).



Op amp power supplies & pins

- Two supply terminals: +ve supply & −ve supply (labeled V_{CC} & V_{EE}; V_{CC+} & V_{CC-} ; or V_{DD} & V_{SS}) connected to circuit ground.
- No ground terminal on the op amp IC.
- Supply voltages may not be equal. Increasing number of applications use single-supply circuits.

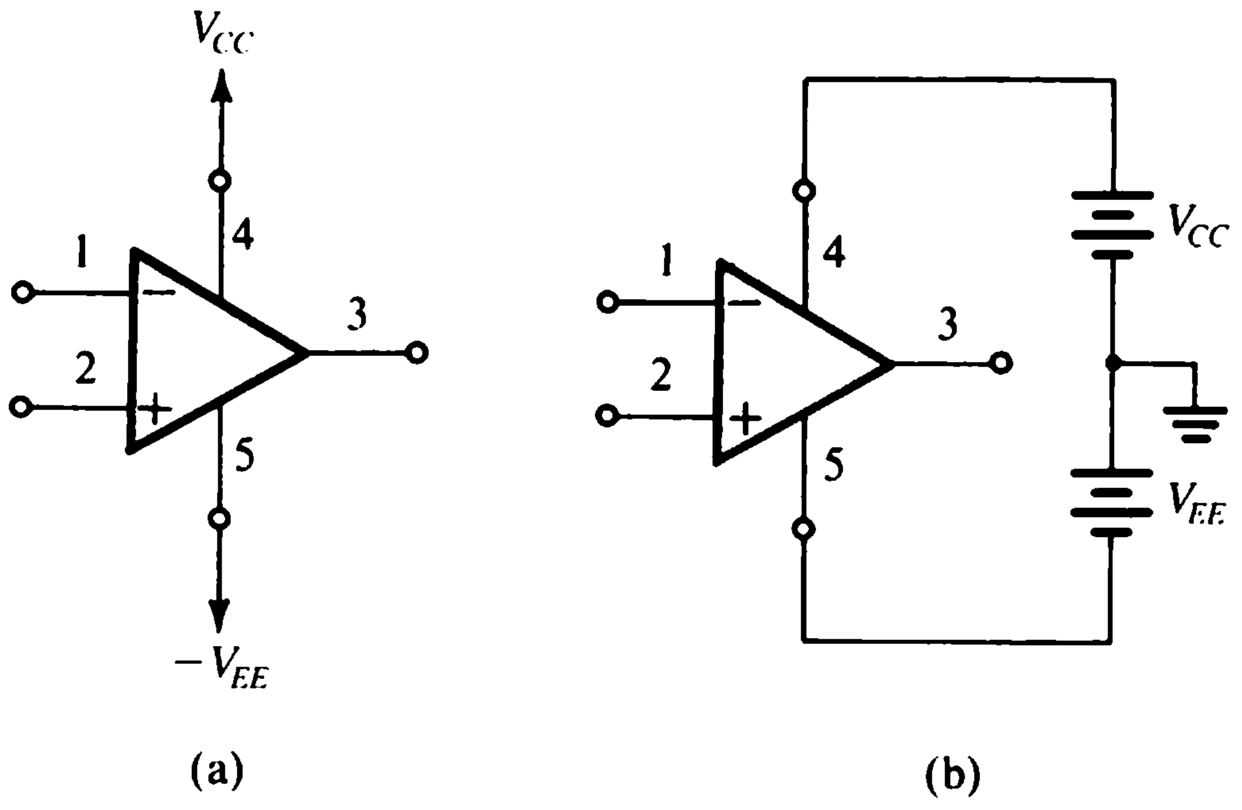


Figure 2.2 The op amp shown connected to dc power supplies.

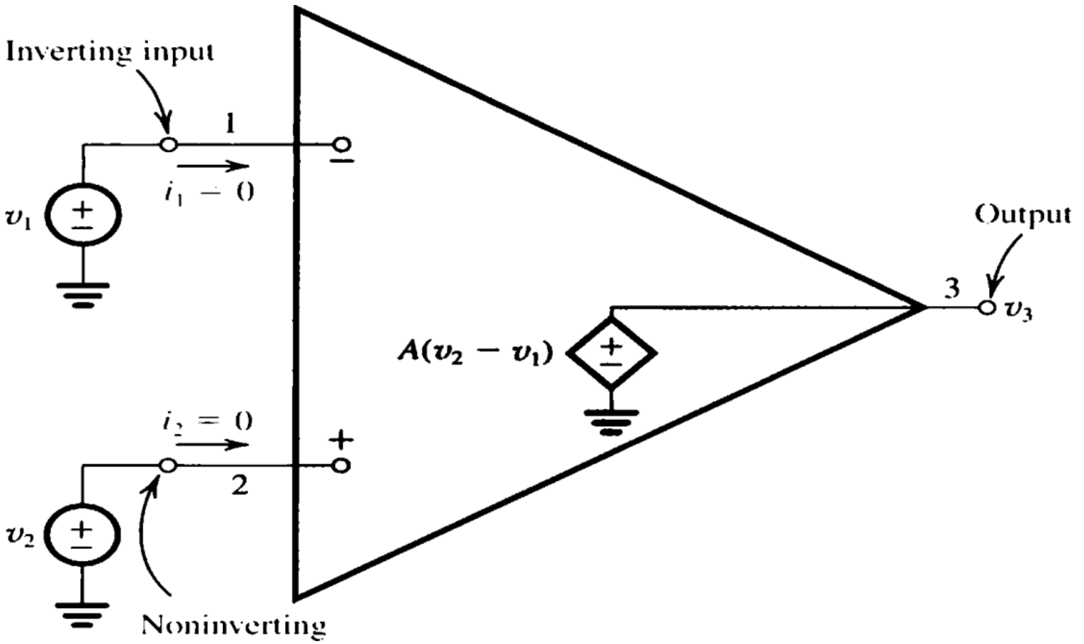
- Minimum number of pins for single op amp: 5, with additional specific-purpose pins (frequency compensation, offset nulling).
- Minimum number of pins for IC with 4 op amps (quad op amp): 14.

Ideal op amp

- **Terminal voltage: voltage between the terminal & ground.**
- **Output voltage = amplification of the difference of two input voltages.**

$v_3 = A(v_2 - v_1)$

- **Differential gain $A \to \infty \Rightarrow$ Finite output voltage for zero difference voltage.**
- **No effect of the voltage common to the two terminals, i.e. $(v_2 + v_1)/2$ on the output.**
- **Zero input currents: infinite input resistances for the two inputs.**
- **v_3 independent of the load current $\Rightarrow$ zero output resistance.**



Difference-mode (DM) & common-mode (CM) signals & gains

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

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

$A \to \infty$ **&** $A_c \to 0$.

Common-mode rejection ratio (CMRR) = $A/A_c \to \infty$

Op amp in linear operation

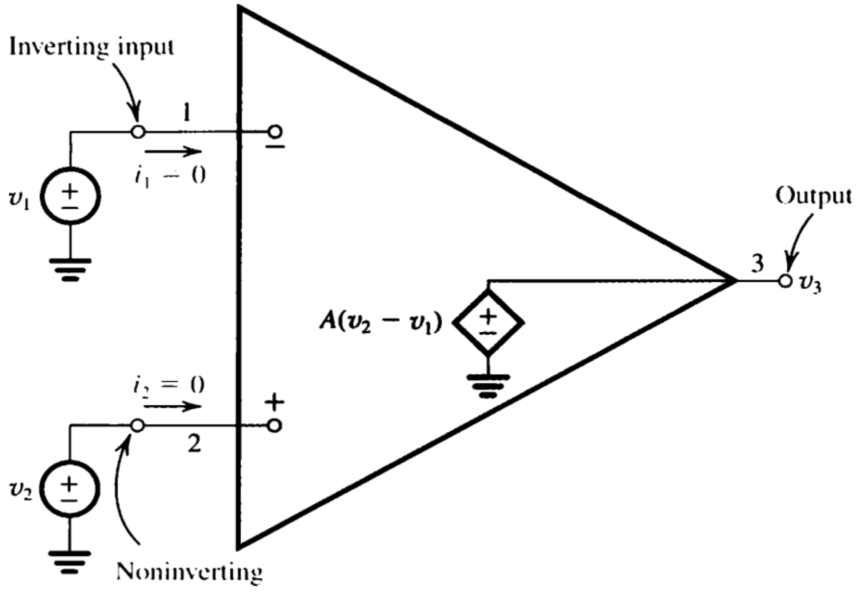
$v_3 = Av_{\mathrm{id}}$

$A \rightarrow \infty$ **& finite output** v_3

$\Rightarrow$ **DM input** $v_{id} = v_2 - v_1 = 0$

Zero current flow into the input terminals

$\Rightarrow$ **Input resistances** $[R_{i1}, R_{i2}] \rightarrow \infty$**:**

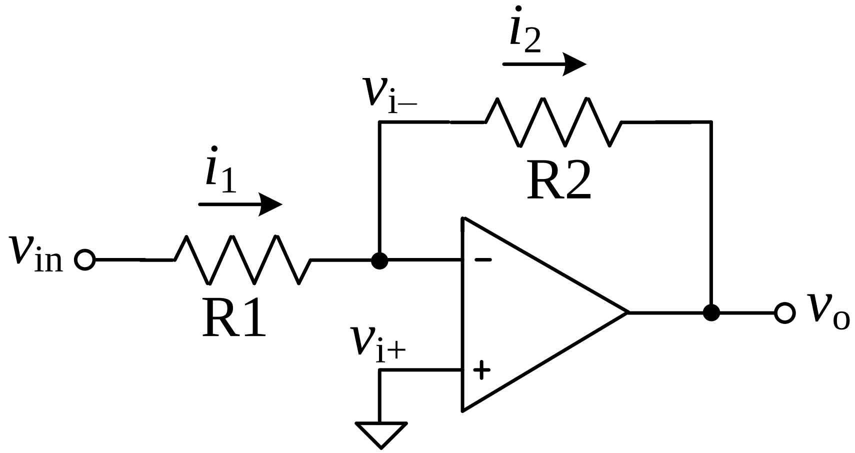


- **Virtual short across the input terminals: zero voltage & zero current flow.**
- **Voltage limits for linear operation**
- **CM input:** $V_{CC+} > V_{ICH} > [v_1, v_2] > V_{ICL} > V_{CC-}$. **Output:** $V_{CC+} > V_{OH} > v_3 > V_{OL} > V_{CC-}$
- **Virtual short is not a basic property of op amp. It has to be satisfied by external circuit & input voltages.**

Input currents may increase and output may be distorted during nonlinear operation.

4. Linear circuits

4.1. Inverting Amplifier Circuit



Virtual short: $v_{i-} = v_{i+} = 0$. $i_1 = i_2$.
$i_2 = i_1 = (v_{in} - v_{i-})/R_1 = v_{in}/R_1$
$v_o = v_{i-} - R_2\, i_2 = -(R_2/R_1)\, v_{in}$

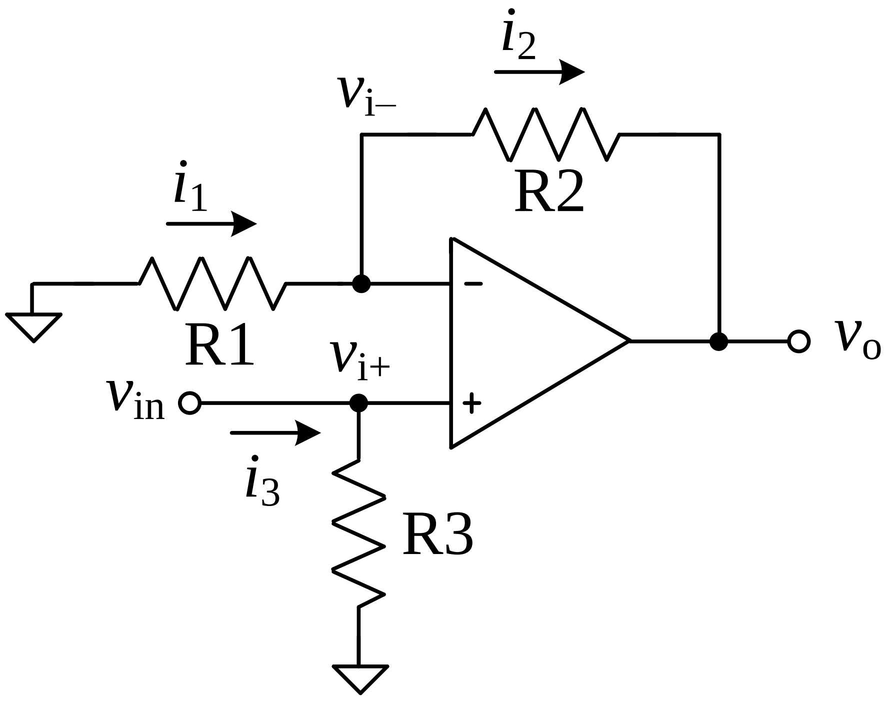
Circuit operation basis: Negative feedback (visited later). It opposes disturbance. Check the circuit operation with virtual short assumption and a disturbance at the −ve input. If v_{i-} increases, it will cause fall in v_o, hence increase in i_2, and hence fall in v_{i-}. Now check the circuit operation with the op-amp input terminals interchanged.

Voltage gain: $A_v = v_o / v_{in} = -R_2/R_1$. Current & power gains depend on load resistance (not shown). Input resistance: $R_{in} = v_{in} / i_1 = R_1$

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

***Example:* $R_1 = 10$ kΩ, $R_2 = 100$ kΩ. $A_v = -10$, $R_{in} = 10$ kΩ . R_{in} can be decreased by connecting a resistor between input and ground.**

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. It 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. Next check with the op-amp input terminals interchanged.

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

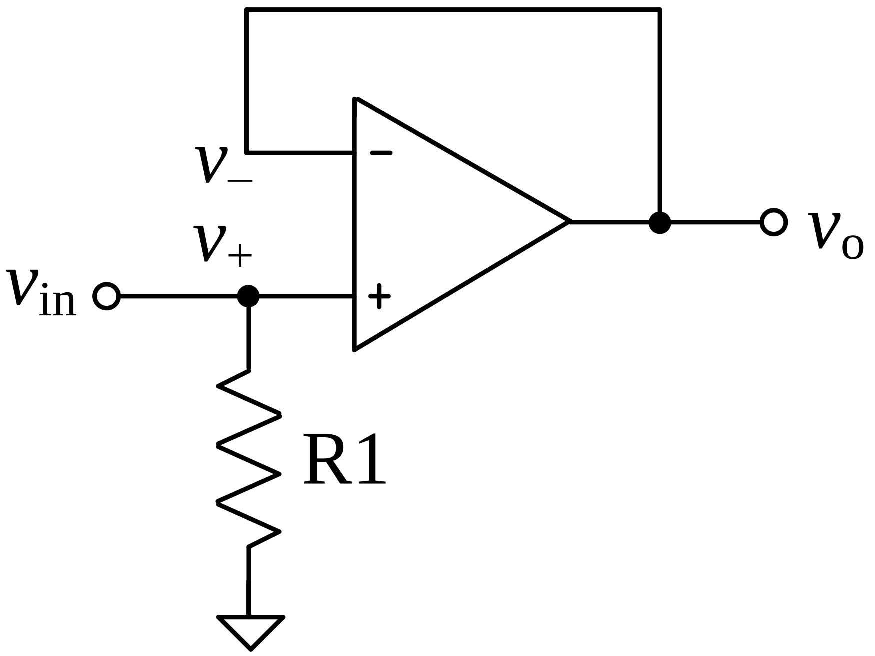
Example: $R_1 = 10\ \text{k}\Omega$, $R_2 = 100\ \text{k}\Omega$, $R_3 = 1\ \text{M}\Omega$, $A_v = 11$, $R_{in} = 1\ \text{M}\Omega$.

4.3. Noninverting Unity Follower Circuit (Unity Buffer)

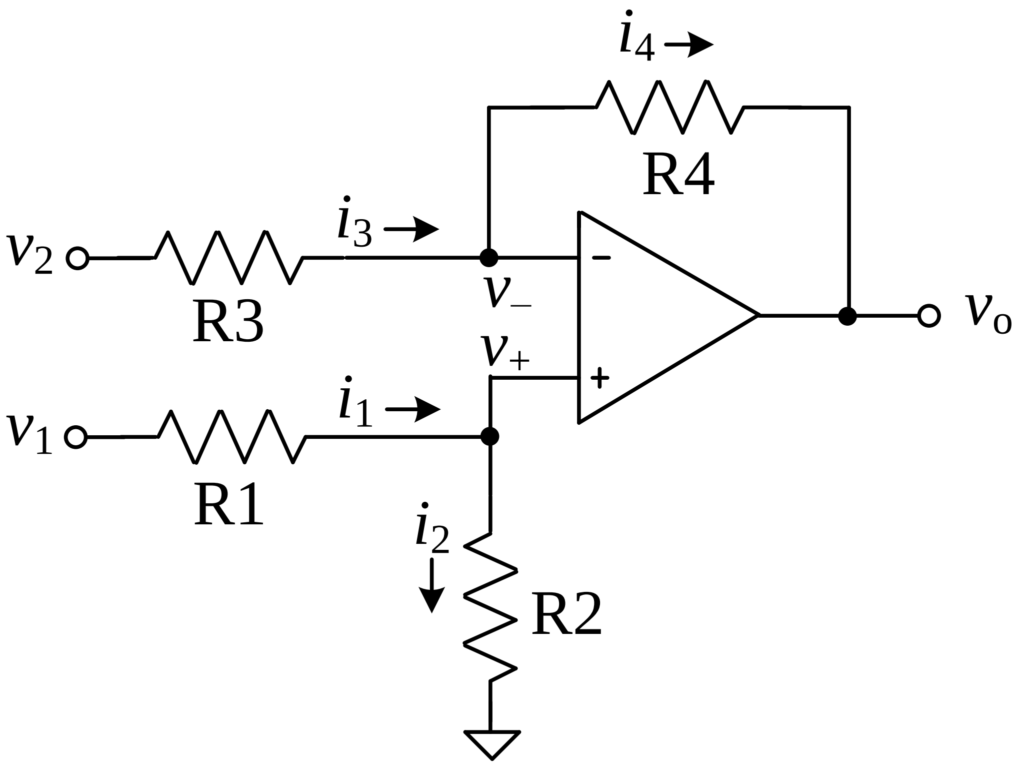
It is a special case of noninverting amplifier with unity voltage gain.

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 & noninverting amplifier for v_1.

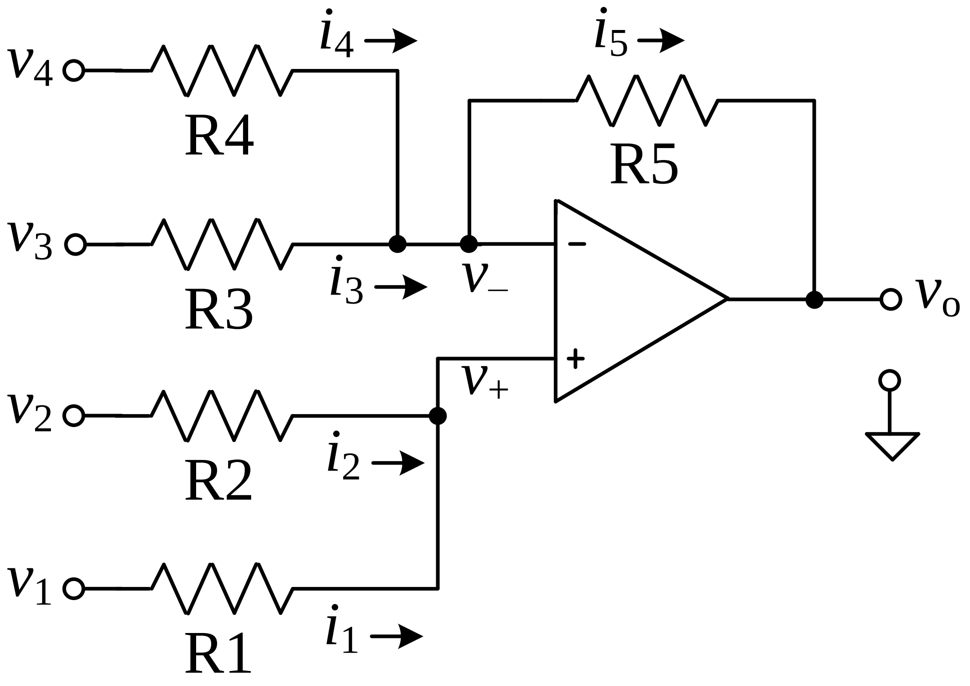
$$v_o = v_1\,[R_2/(R_1+R_2]\,[1+R_4/R_3] - v_2\,[R_4/R_3]$$
$$= v_1\,[\alpha/(1+\alpha)][1+\alpha] - v_2\,[\alpha] = \alpha\,(v_1 - v_2)$$

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

- **Precise differential gain. Resistance matching needed. Difficult gain control. Unequal input resistances.**
- **A voltage (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

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

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

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

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

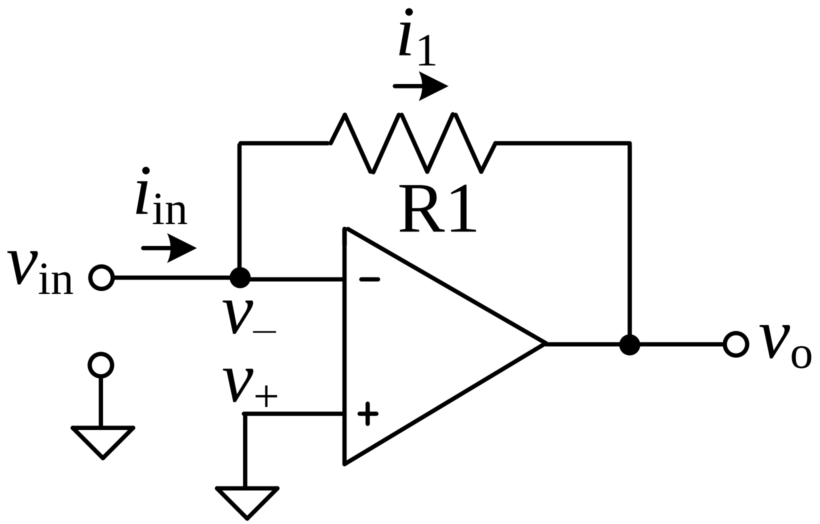
$A_3 = -R_5/R_3$, $A_4 = -R_5/R_4$

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

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

- **It has convenient inverting gain controls, independently by R_3 & R_4, together by R_5. Non-inverting gain controls are more difficult. Circuit can be extended for multiple inputs.**
- **Mostly used as multi-input inverting summer or two-input difference amplifier.**

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



Virtual short assumption

$v_{i-} = v_{i+} = 0$ & $i_1 = i_{in}$

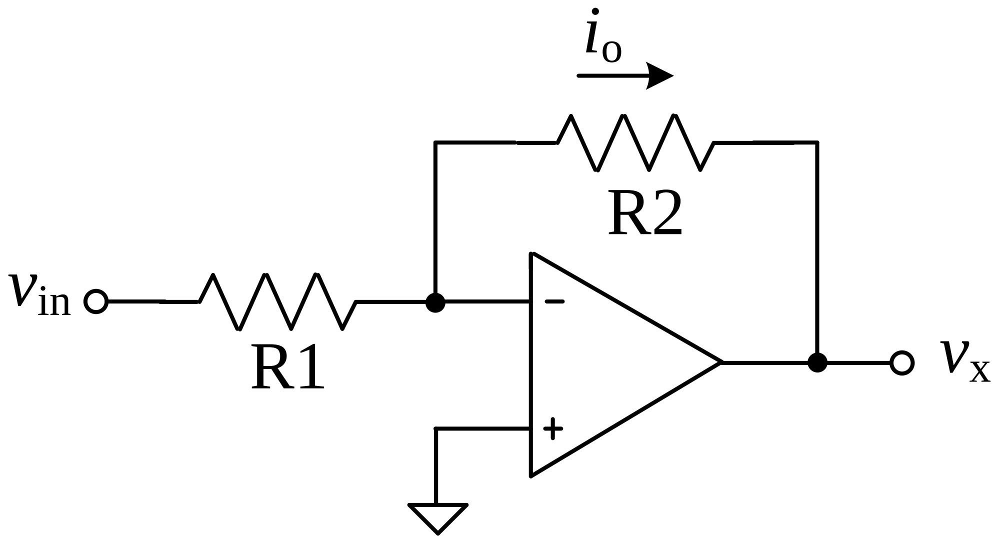
$v_O = v_{i+} - R_1 i_{\text{in}} = -R_1 i_{\text{in}}$

$R_{in} = 0$

Application: **I/V converter for input current with ground as return. Another circuit with three op amps is needed for sensing current not having ground return.**

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

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



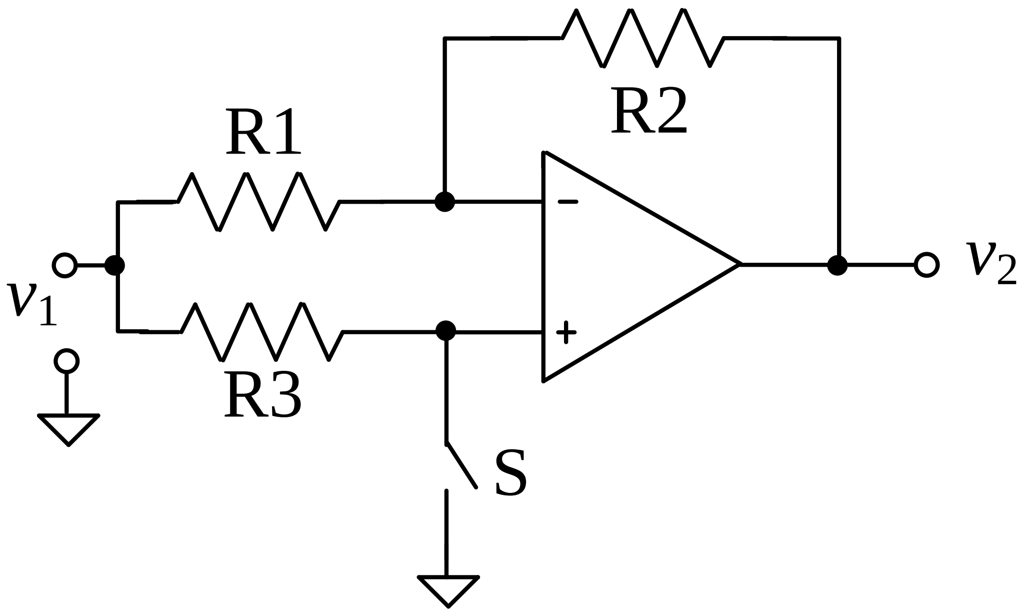
$\boldsymbol{i_O = v_{IN}/R_1}$
$\boldsymbol{R_{in} = R_1}$
$\boldsymbol{v_X = -R_2\, i_O}$

- **R_2 is limited by voltage swing at v_X. This circuit is for a floating load (no restriction on connection of either terminal). Another circuit is needed for grounded load (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: $v_2 = (-R_2/R_1)\, v_1 = -\, v_1$

$A = -1$

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

$A = +1$

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

4.9. Practical Op Amp

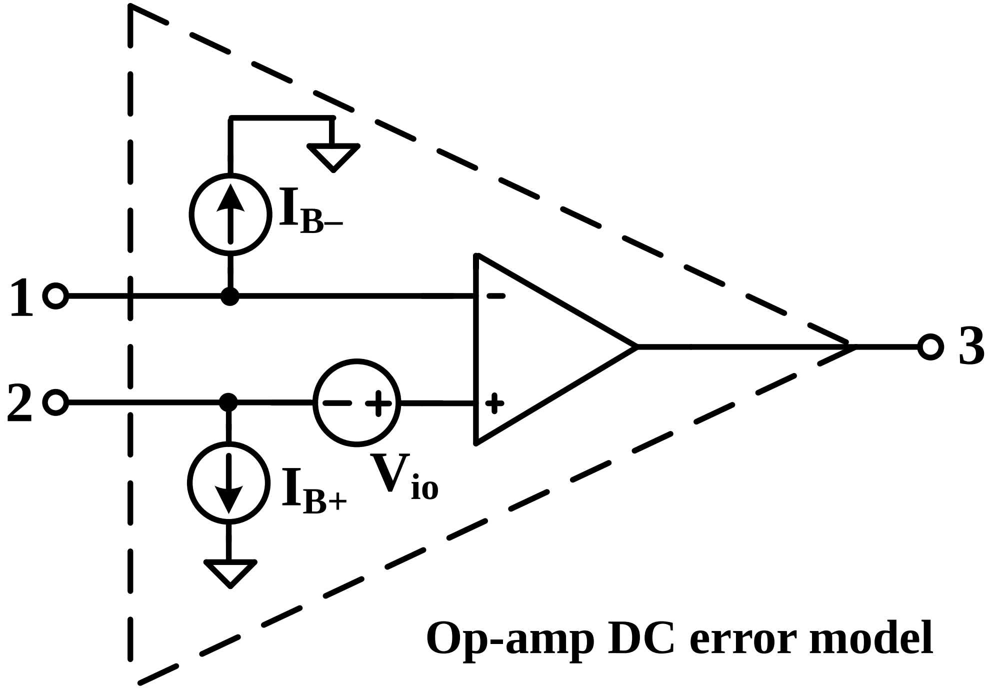
Op-amp linear operation has limits for CM input voltage, output voltage, & output current (due to DC supplies & internal circuit)

- **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.**



Op-amp DC error model

- **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).**

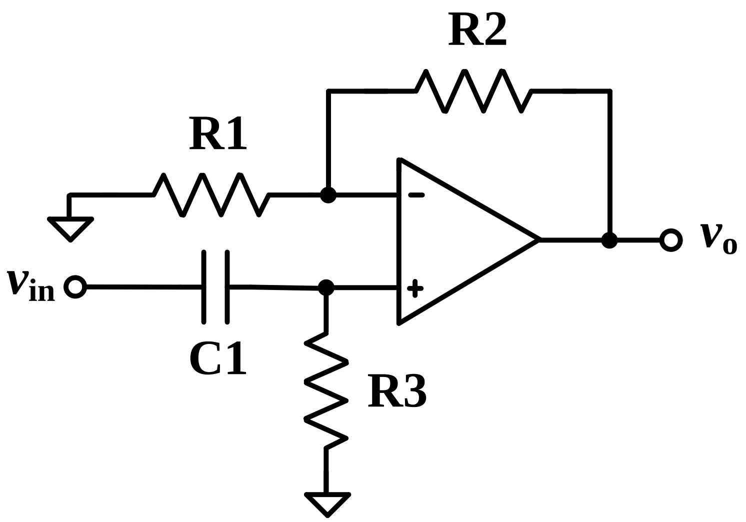
4.10. AC Amplifier Circuits

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}. Circuit must have a DC current path from each op-amp input terminal to the ground.

AC Noninverting Amplifier

$1/(2\pi f_{min} C_1) << R_3$

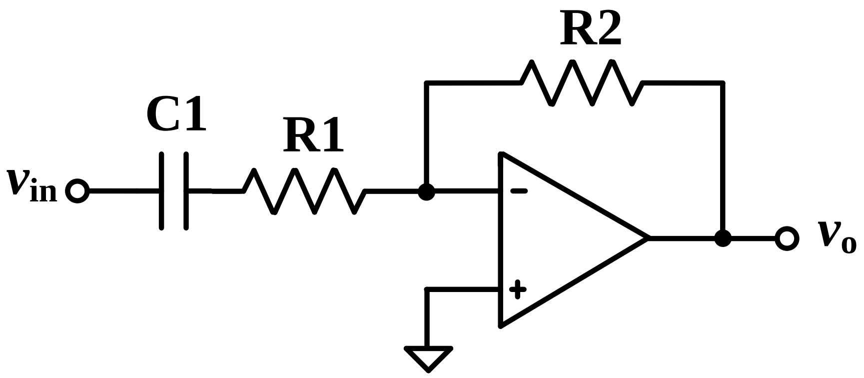
$A_v = 1 + R_2/R_1.$ $\quad\quad R_{in} = R_3$



AC Inverting Amplifier

$1/(2\pi f_{min} C_1) << R_1$

$A_v = -R_2/R_1.$ $\quad\quad R_{in} = R_1$



5. Feedback Amplifier & Oscillator

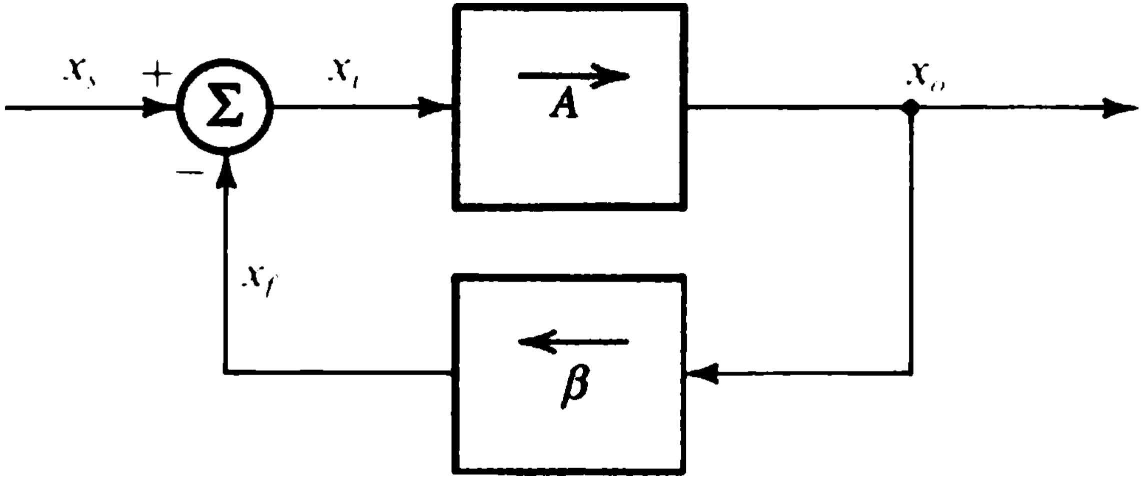
• ***Feedback:*** **Addition of a fraction of the output to the input for desirable system behavior.**

• ***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.***

General Feedback Structure



• Signal-flow diagram, quantities may be voltage or current.

• Basic amplifier: output x_o, input x_i,
open-loop gain A. $\Rightarrow x_o = Ax_i$

• Feedback network: feedback signal x_f, feedback factor β. $\Rightarrow x_f = \beta x_o$

• Feedback amplifier with an adder for subtracting the feedback signal x_f from the source signal x_s.

• Basic amplifier input $x_i = x_s - x_f$. $\Rightarrow x_o = Ax_i = A(x_s - x_f) = A(x_s - \beta x_o)$ $\Rightarrow x_o(1 + A\beta) = Ax_s$

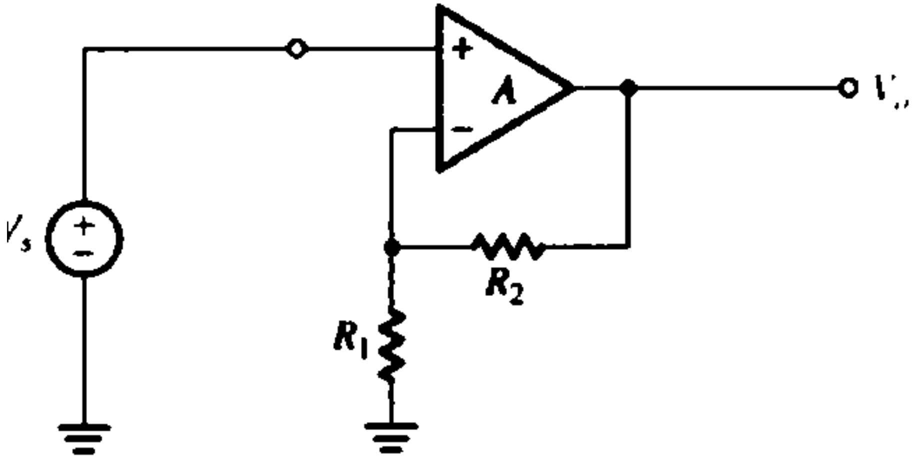
• Loop-gain = $A\beta$

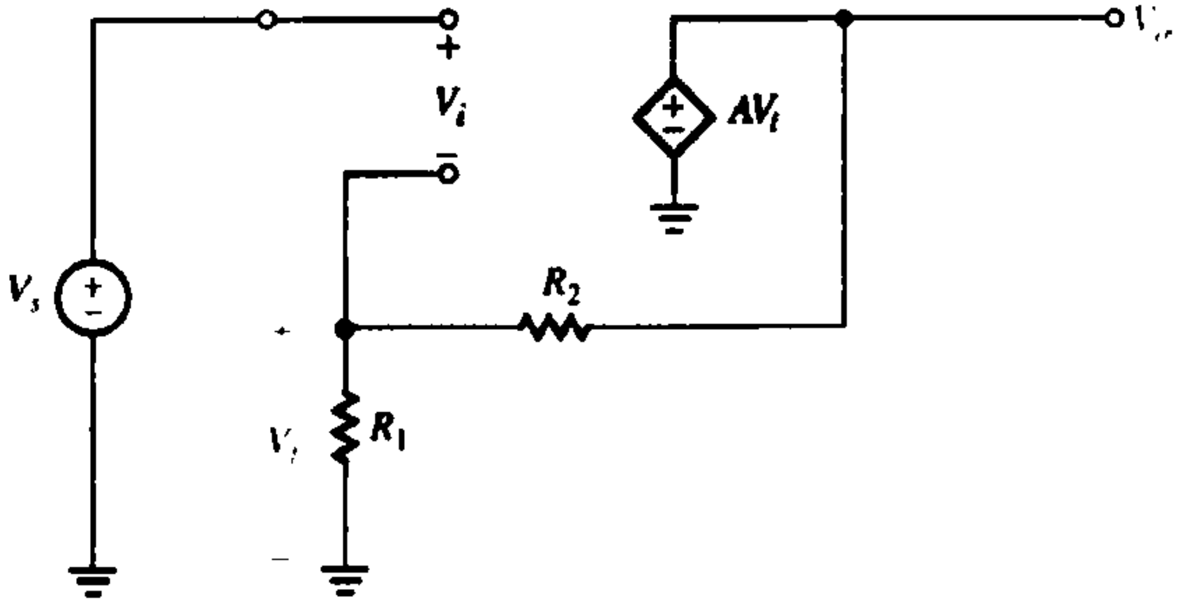
• Closed-loop gain: $A_f = \dfrac{x_o}{x_s} = \dfrac{A}{1+A\beta} = \dfrac{1}{\beta}\,\dfrac{1}{1 + 1/(A\beta)}$ $\Rightarrow A_f \approx \dfrac{1}{\beta}$ for $A\beta >> 1$, or $A >> 1/\beta$.

• Large loop-gain $\Rightarrow$ closed-loop gain determined by the feedback factor.

As A depends on electronic device parameters, it may have large variation. β depending on passive components can be precise, resulting in precise closed-loop gain. Closed-loop gain error decreases with increasing loop-gain.

Noninverting Amplifier as a Negative Feedback Amplifier (circuit & feedback model)





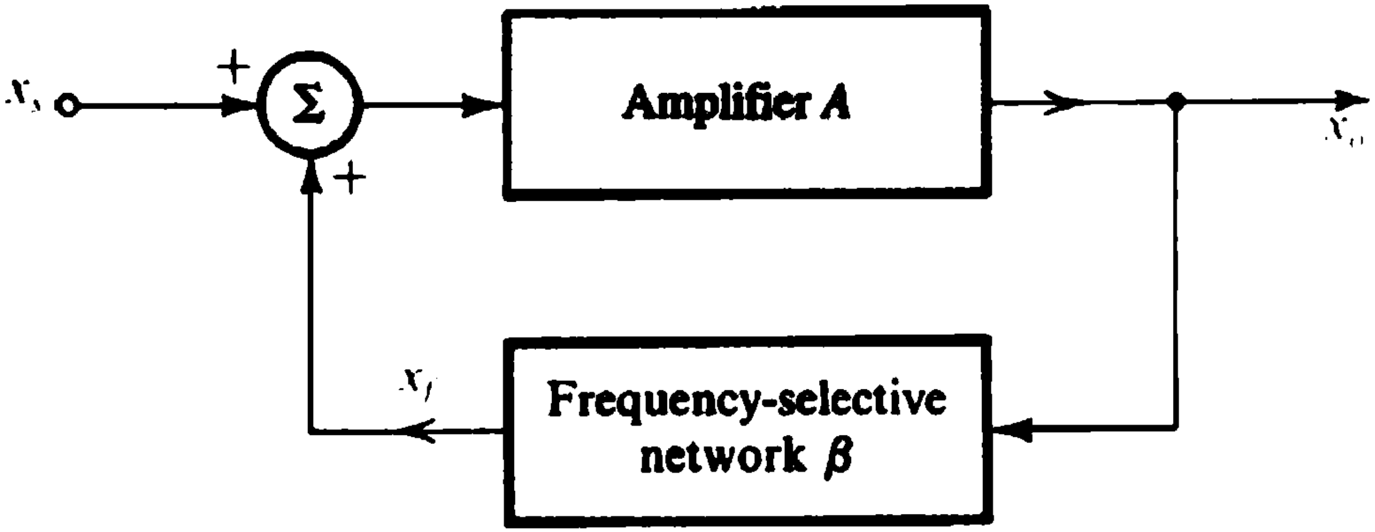
Open-loop gain = op-amp differential gain. Feedback factor is set by resistive attenuator (R1, R2). Feedback subtraction is at the op-amp differential input.

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

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

Amplifier, +ve feedback, frequency-selective network



Closed-loop gain

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

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

Oscillator circuit has 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).

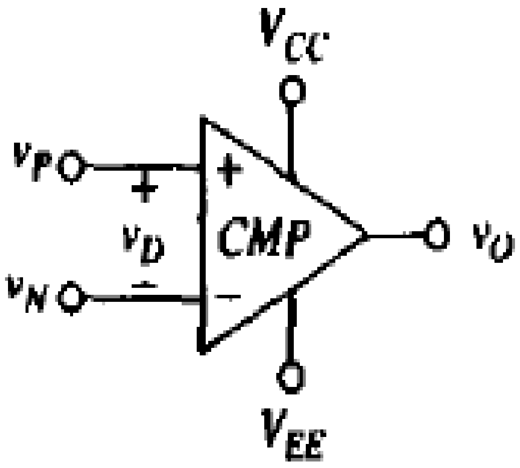
6. Nonlinear Circuits

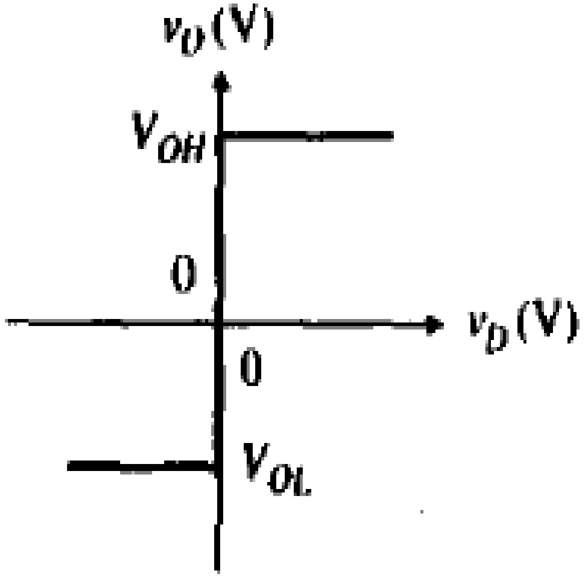
Voltage Comparator

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-}.

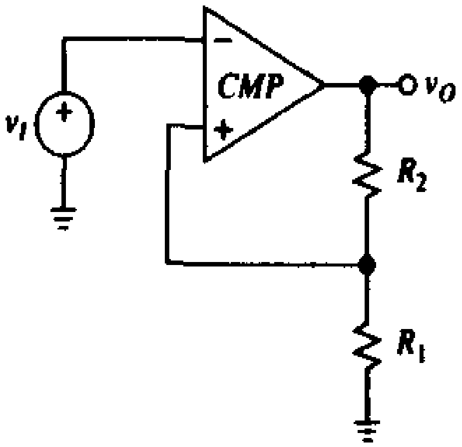
• A comparator is designed for very low input currents despite large differential input voltage. Buffers at each input before the differential high-gain. An op amp can be used as a comparator with due consideration for finite differential input voltage.

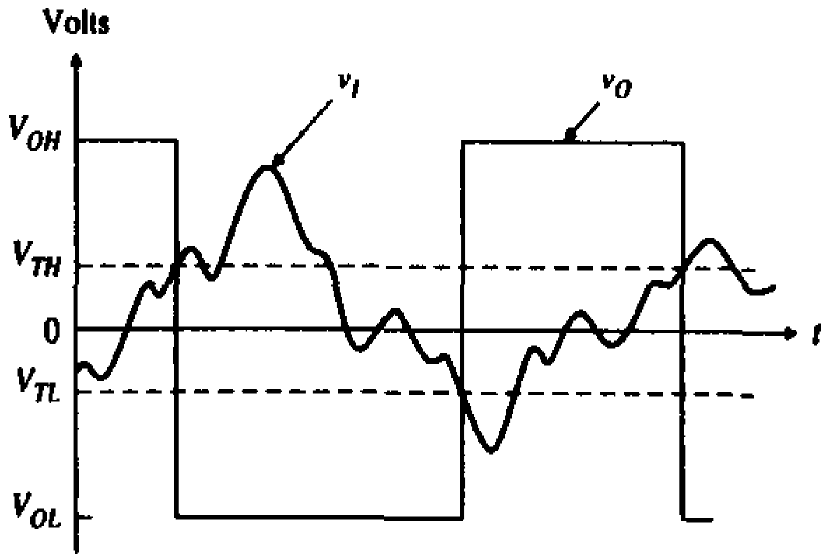
Schmitt Trigger

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

- **Inverting Schmitt trigger: clockwise hysteresis.**

- **Noninverting Schmitt trigger: counterclockwise hysteresis.**





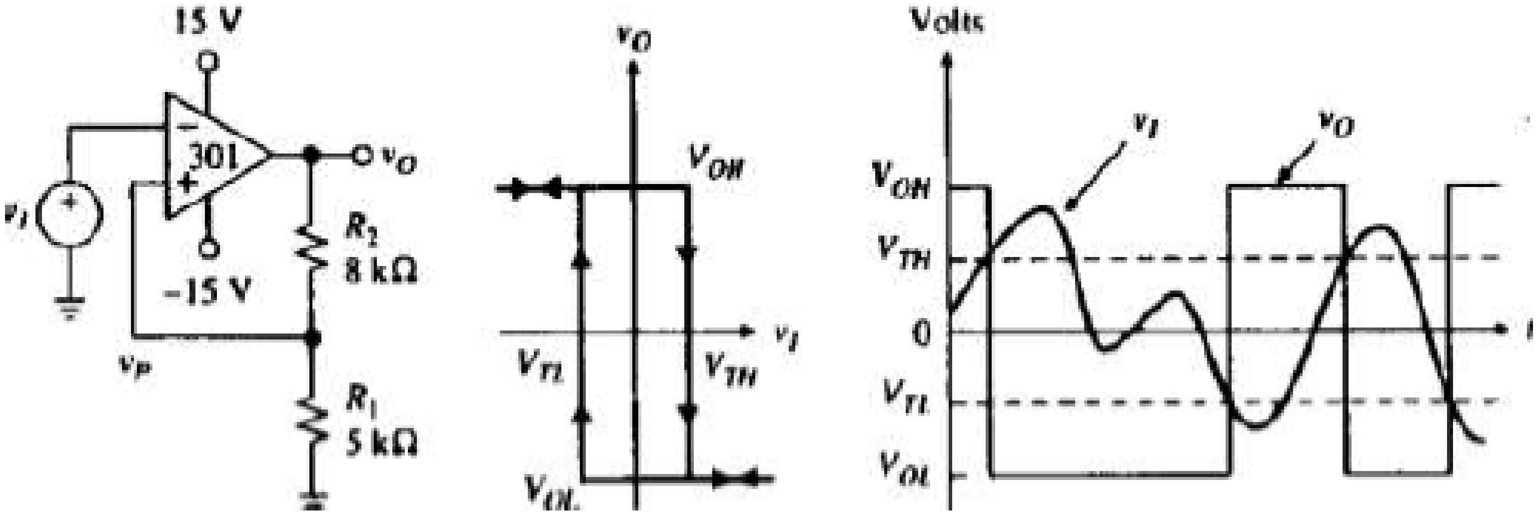
Applications: **Chatter elimination, waveform generation, signal processing.**

Inverting Schmitt trigger

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

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

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

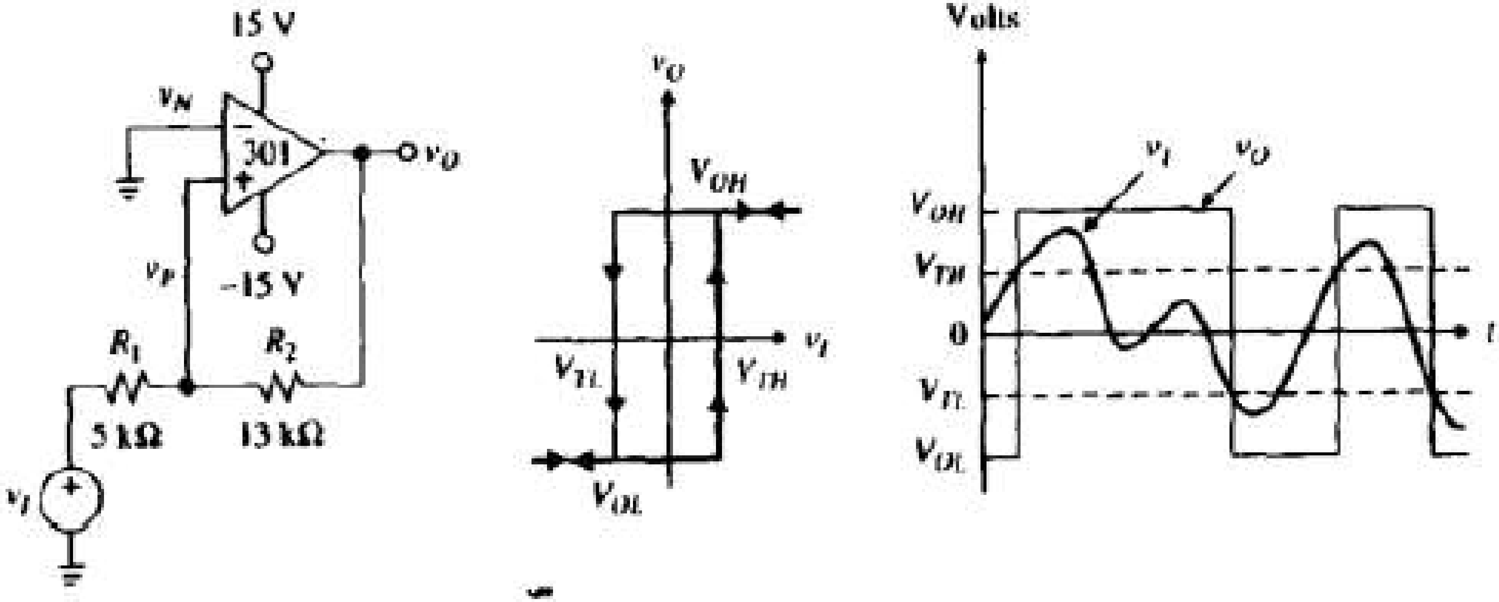


Noninverting Schmitt trigger

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

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

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



That's all for now.

Thanks.