Academic Year: 2023-2024, Semester: I

Course: MS 101

EE Lectures: 04 & 05

Operational Amplifier Circuits

- Signal basics
- Amplifiers
- Op amp
- Linear circuits
- Feedback amp & oscillator
- Nonlinear circuits

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.

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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.

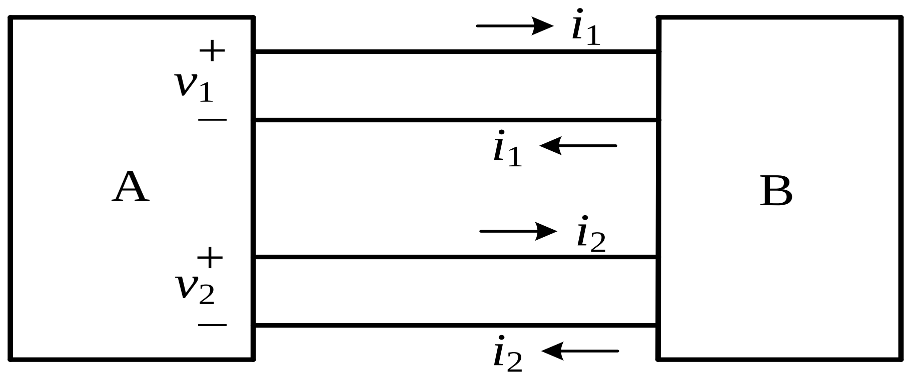
Electric signal: Time-varying voltage or current waveform on a port (2 terminals or a pair of conductors).

Differential signals: Each signal needs two conductors.

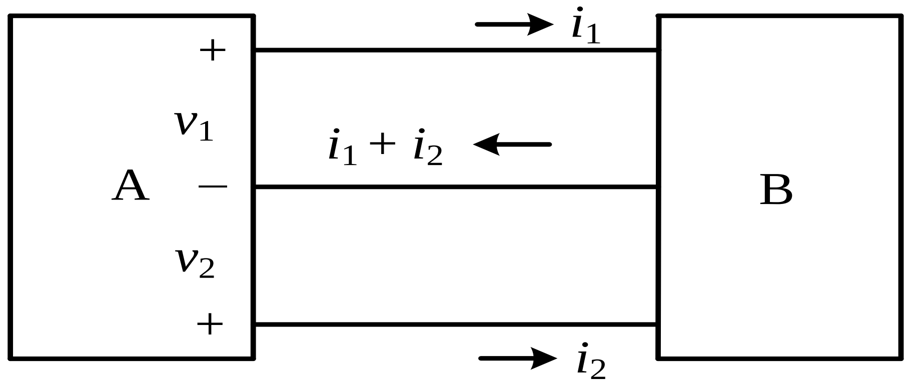
Single-ended signals: Several signals share a common reference in case of voltage signals, & a common return (in case of current signals).

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.

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.



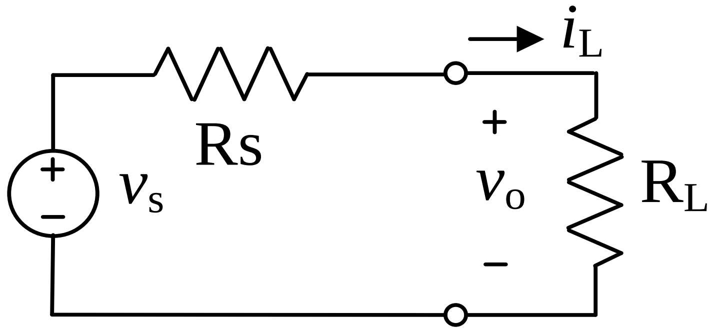
Two differential signals (each with two conductor)



Two single-ended signals (common reference & return)

Two signal representations

Voltage source model
(Thevenin form)

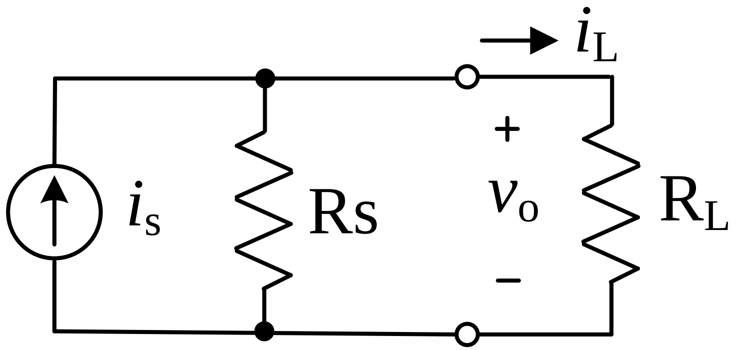


$$i_L = \frac{v_s}{R_s + R_L}$$

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

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

Current source model
(Norton form)



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

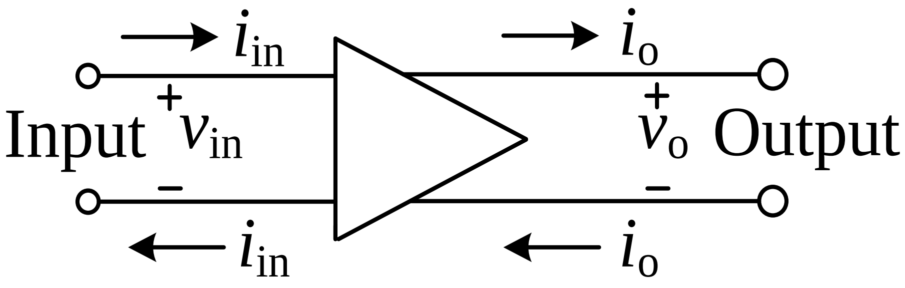
$$i_L = \frac{v_o}{R_L} = i_s \left(\frac{R_s}{R_s + R_L} \right)$$

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

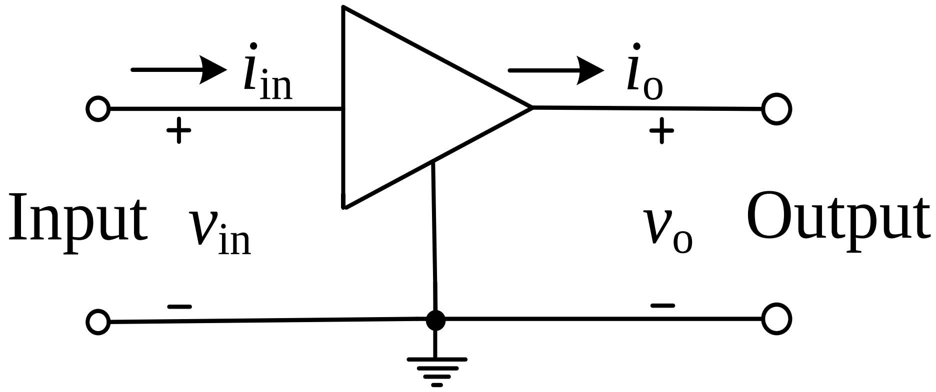
Preferred representation
$R_s << R_L$: voltage source. $R_s >> R_L$: current source.

2. Amplifiers

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



Amplifier with diff. input & diff output



Amplifier with grounded input & grounded output

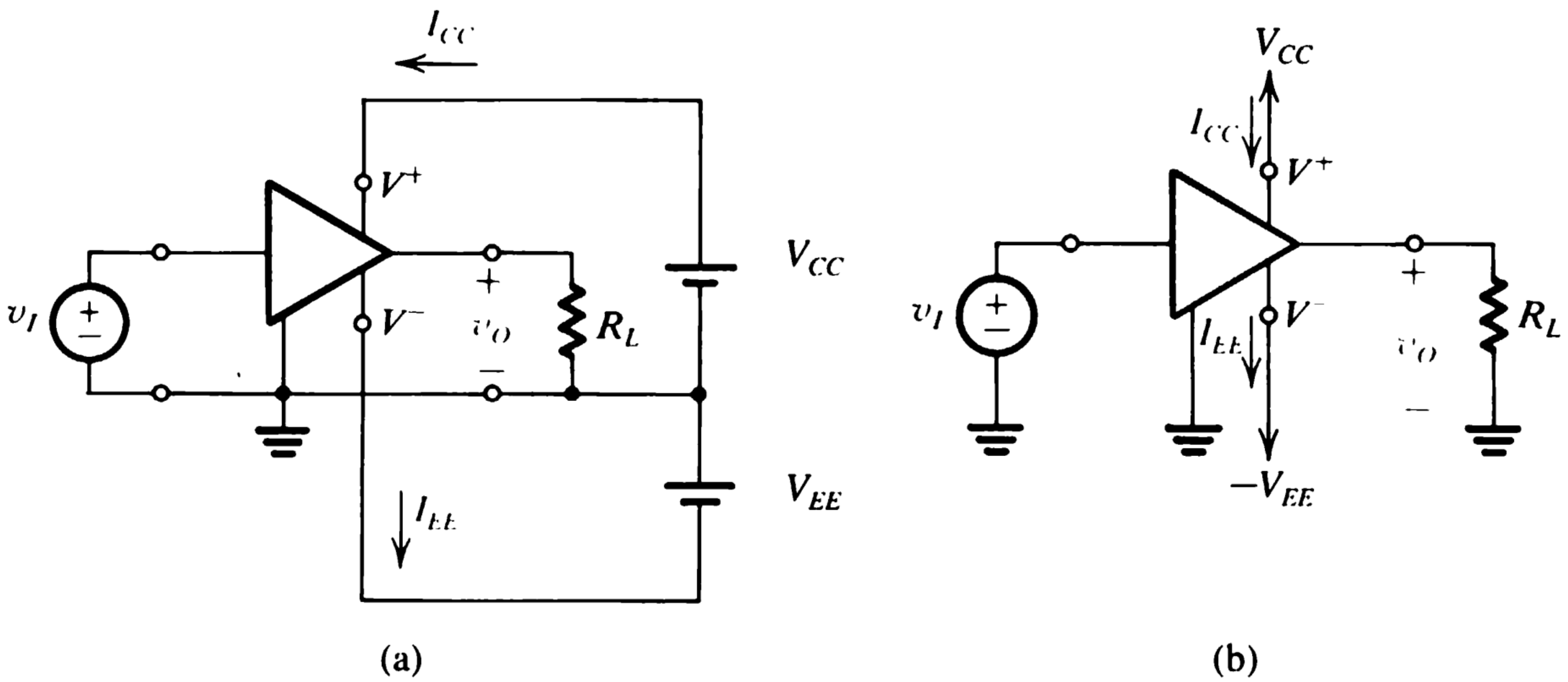
- Voltage gain $A_v = v_o / v_{in}$
- Current gain $A_i = i_o / i_{in}$
- Power gain $A_p = (v_o i_o)/(v_{in} i_{in}) = A_v A_i$. Amplification: $A_p > 1$. Attenuation: $A_p < 1$

Amplifier power supplies: 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 sources connected to the circuit ground. Supplies need not be equal

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

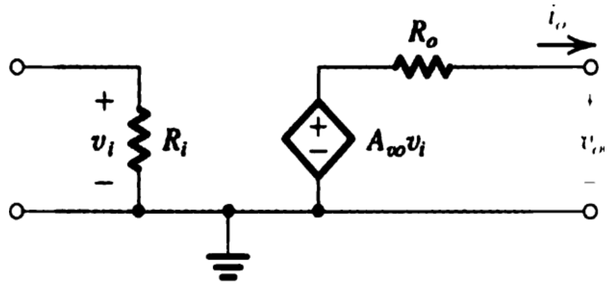
Input & output voltage swings are limited by supply voltages & circuit.



Circuit diagrams: (a) diagram with explicit connections , (b) simplified diagram.

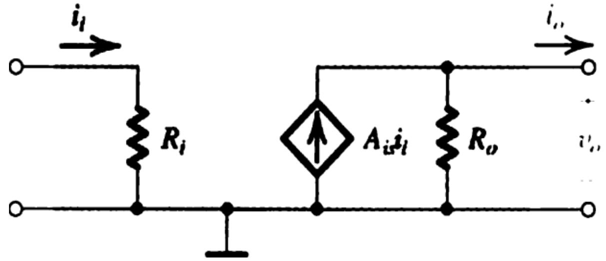
Amplifier types (single-ended): dependent sources

Voltage amp (VCVS)



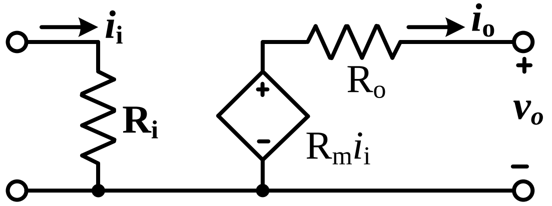
Open-circuit voltage gain: A_{vo}
Ideal: $R_i = \infty$, $R_o = 0$

Current amp (CCCS)



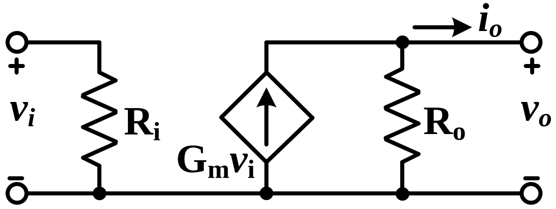
Short-circuit current gain: A_{is}
Ideal: $R_i = 0$, $R_o = \infty$

Trans-resistance amp (CCVS)



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

Trans-conductance amp (VCCS)



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

Differential amplifier

Differential mode (DM) input

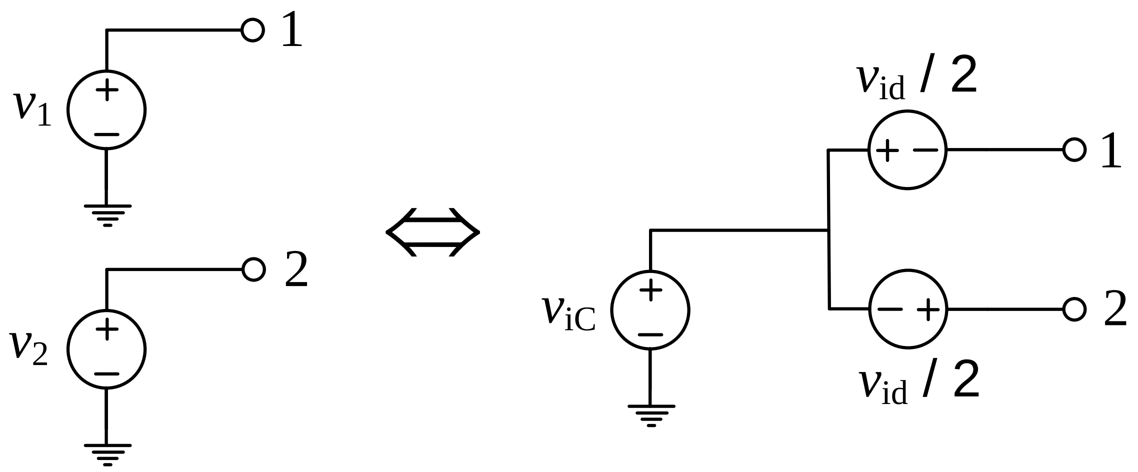
$v_{id} = v_2 - v_1$

Common mode (CM) input

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

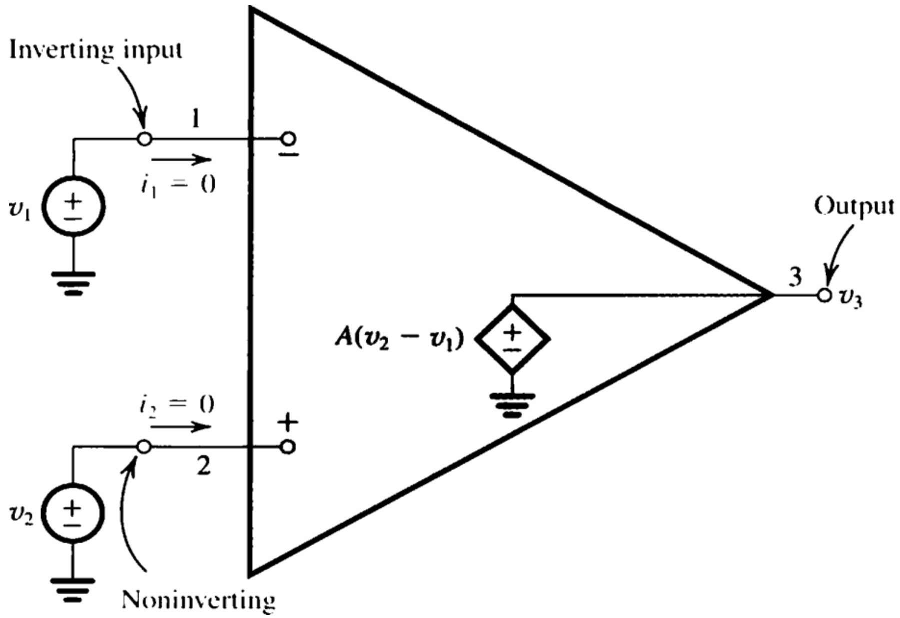
Input voltages in terms of DM and CM inputs

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



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.

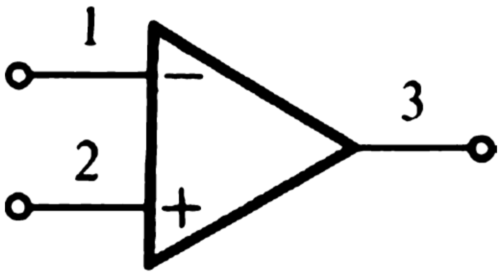
• Main objective: Circuit performance parameters decided by passive components & nearly independent of electronic device parameters.

Op amp circuit symbol (simplified)

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

• 3 single-ended ports with the circuit ground (Gnd) as the common terminal (implied, not shown in the symbol).

• Inverting input v_{i-}: 1-Gnd. Non-inverting input v_{i+}: 2-Gnd. Output v_o: 3-Gnd.



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 Gnd. Op amp itself does not have Gnd terminal.

• Supply voltages may not be equal. Many applications use single-supply circuits.

• Minimum number of pins for single op amp: 5 (inputs:2, output:1, supplies: 2).

• Additional specific-purpose pins: frequency compensation, offset nulling.

• Minimum number of pins for chip with 4 op amps (quad op amp): 14.

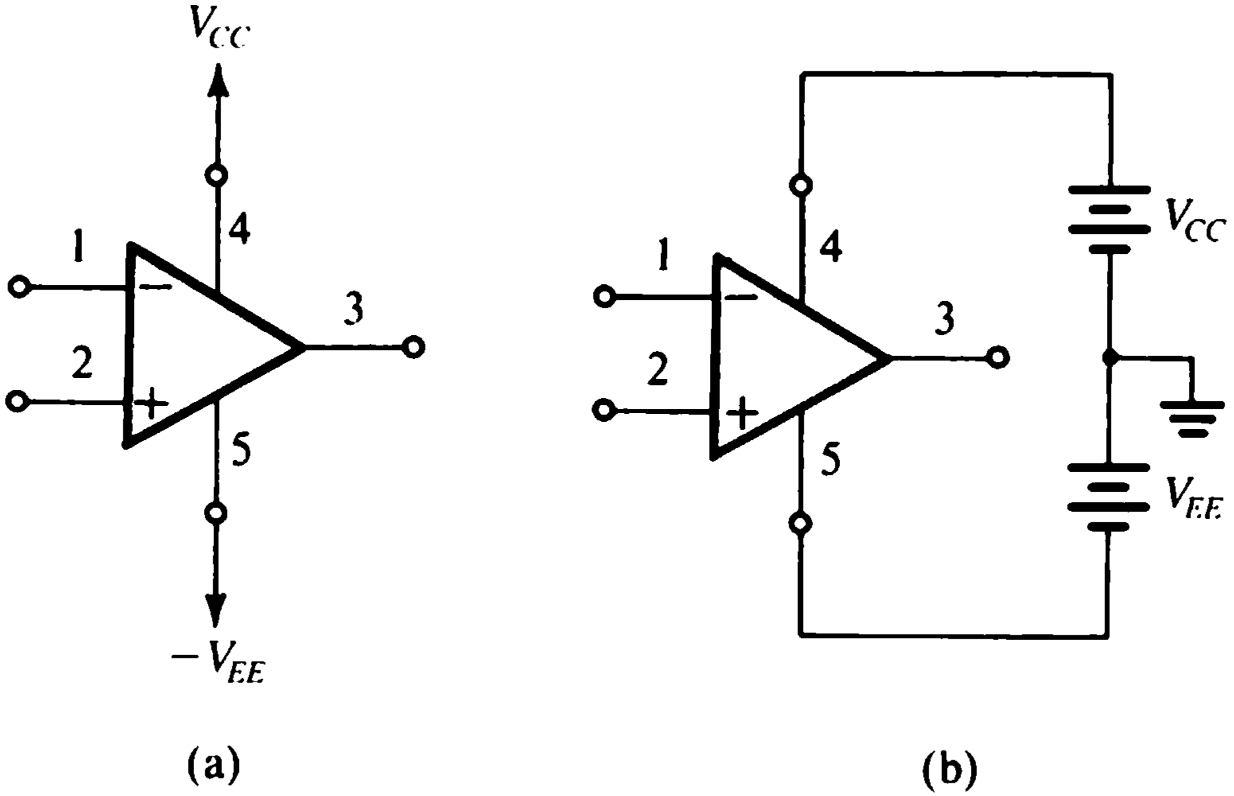
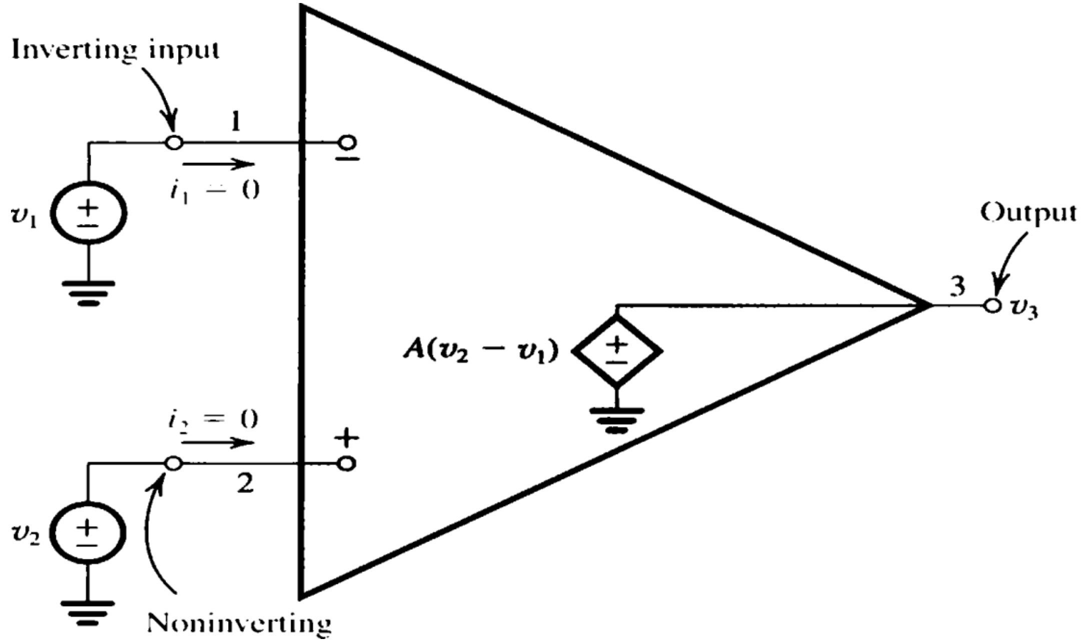


Figure 2.2 The op amp shown connected to dc power supplies.

Input-output relation

- Terminal voltage: voltage between the terminal & Gnd.
- Difference-mode (DM) input $v_{id} = v_2 - v_1$.
- Common-mode (CM) input $v_{ic} = (v_2 + v_1)/2$.
- Output voltage $v_3 = A_d v_{\mathrm{id}} + A_c v_{\mathrm{ic}}$.
- DM gain: A_d. CM gain: A_c.
- Common-mode rejection ratio (CMRR) = A_d / A_c.



Ideal op amp

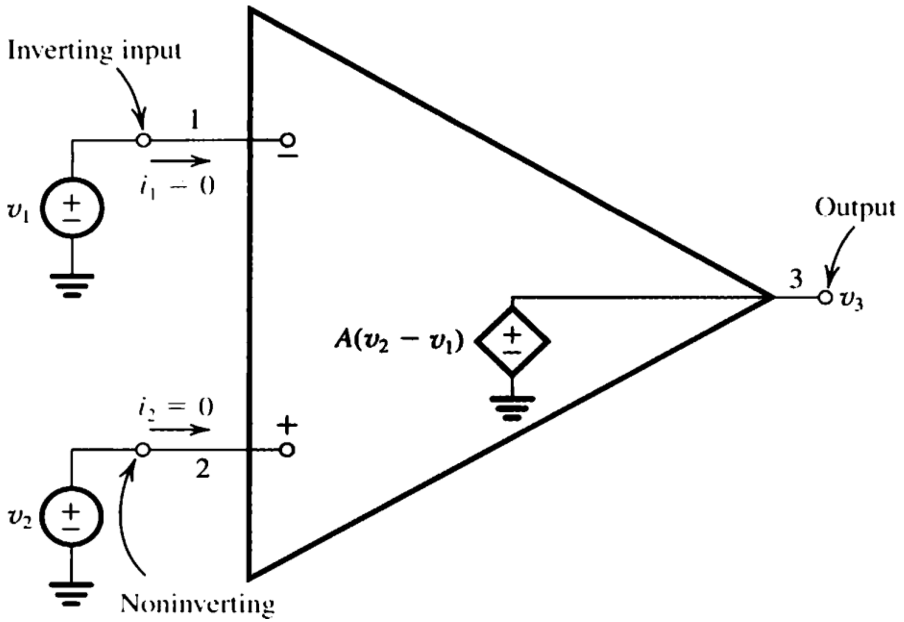
- $A_d \rightarrow \infty$. $A_c \rightarrow 0$. $v_3 = A_d(v_2 - v_1)$

DM input amplification with no effect of CM input. Finite output voltage obtained with zero DM input.

CMRR $= A_d / A_c \rightarrow \infty$.

- Infinite input resistances for the two inputs (zero input currents) .
- Zero output resistance (output voltage independent of the load current).

Op amp in linear operation



- $v_3 = A_d v_{\text{id}}$

For finite output v_3 and $A_d \to \infty$, DM input $v_{\text{id}} = v_3/A_d \to 0$.

- Input resistances R_{i1}, $R_{i2} \to \infty \Rightarrow$ zero input currents.

- Zero voltage across the input terminals with zero input currents is known as "virtual short" across the input terminals.

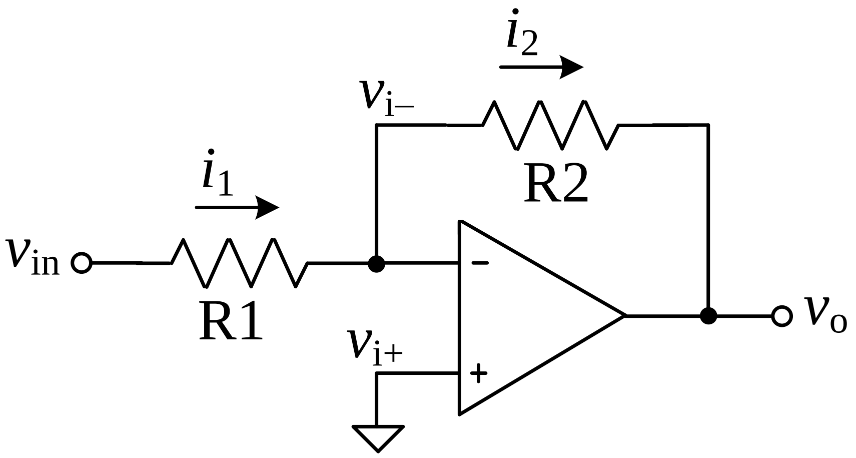
- Virtual short condition is very useful in analyzing linear op amp circuits.

- Virtual short is applicable only during linear operation, & the conditions for it have to be satisfied by external circuit & input voltages. 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: $V_{CC+} > V_{OH} > v_3 > V_{OL} > V_{CC-}$.

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

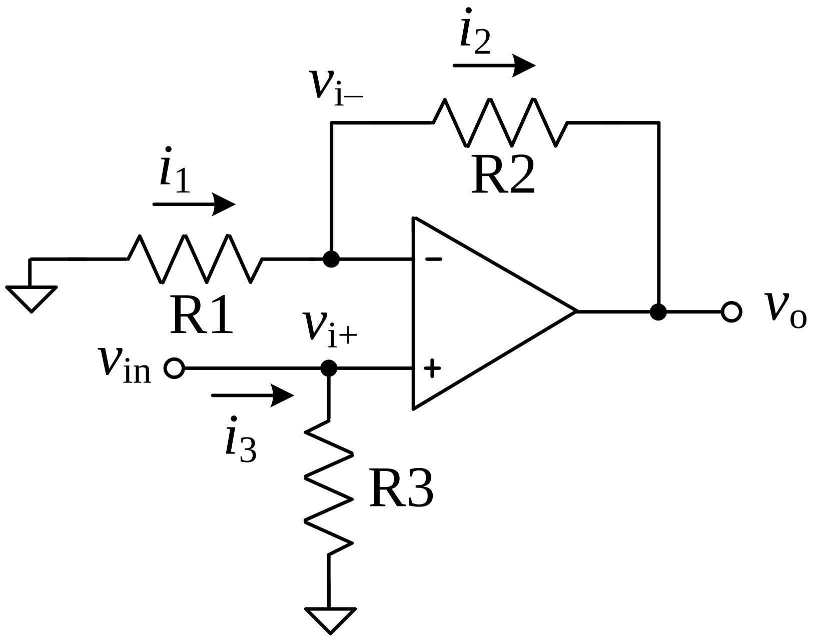
Circuit operation basis: Negative feedback (visited later), which opposes disturbance. Check the circuit operation with virtual short assumption and a disturbance at the −ve input. If v_{i-} increases, v_o decreases, i_2 increases, v_{i-} decreases, leading to virtual short restoration. If the op-amp 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 by connecting a resistor between input and ground.

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

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

4.2. Non-inverting 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 non-inverting gain with high, moderate, or low R_{in}.

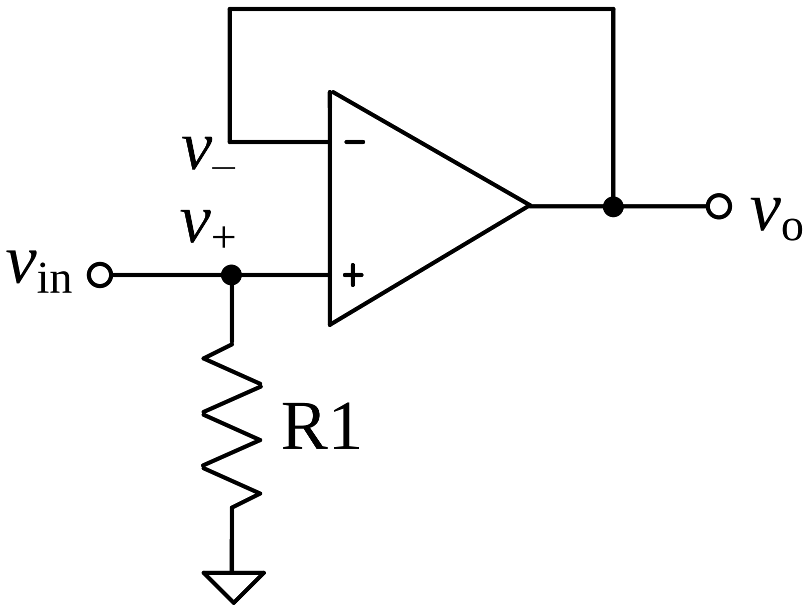
Example: $R_1 = 10\ \text{k}\Omega$, $R_2 = 100\ \text{k}\Omega$, $R_3 = 1\ \text{M}\Omega$, $A_v = 11$, $R_{in} = 1\ \text{M}\Omega$.

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

It is a special case of non-inverting 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.

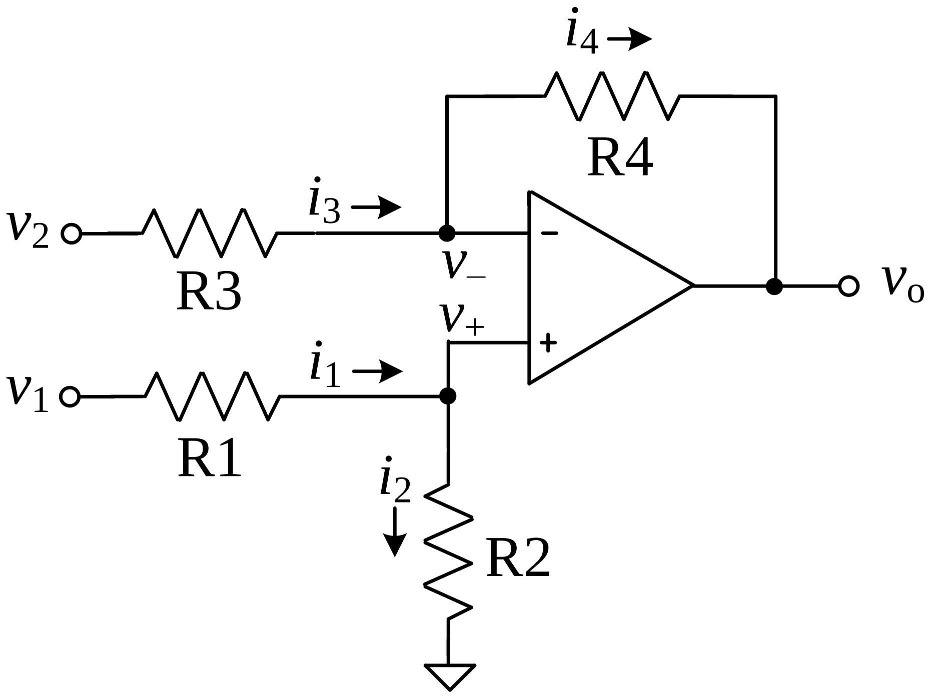


4.4. Difference Amplifier Circuit

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 $A_d = \alpha$.

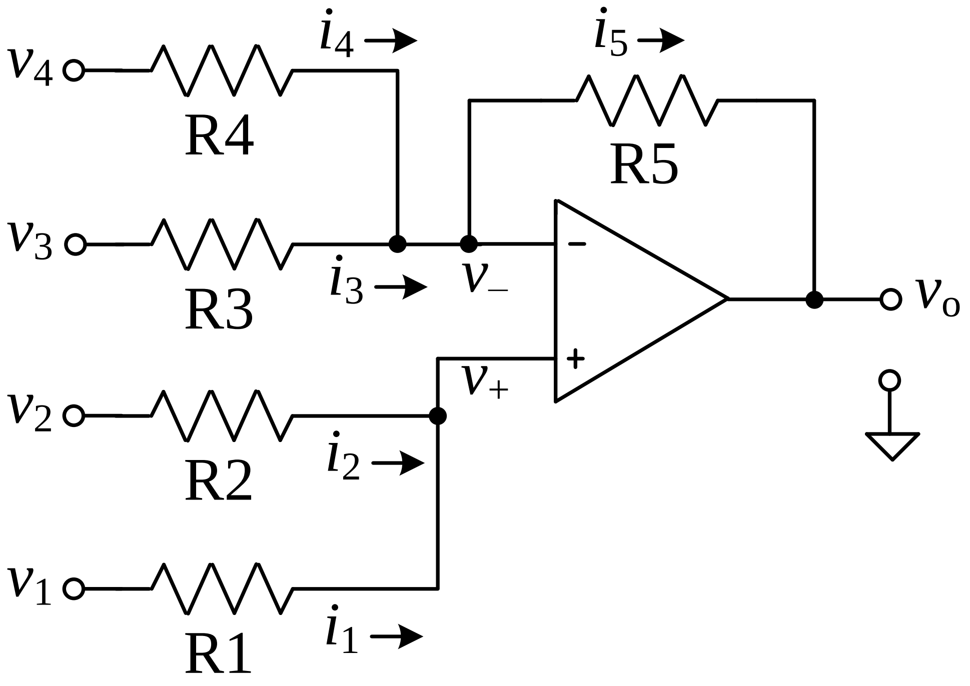
CM gain $A_c = 0$

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

- Precise differential gain. Resistance matching needed. Difficult gain control. Unequal input resistances.
- A voltage (DC bias) v_3 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.

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

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

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

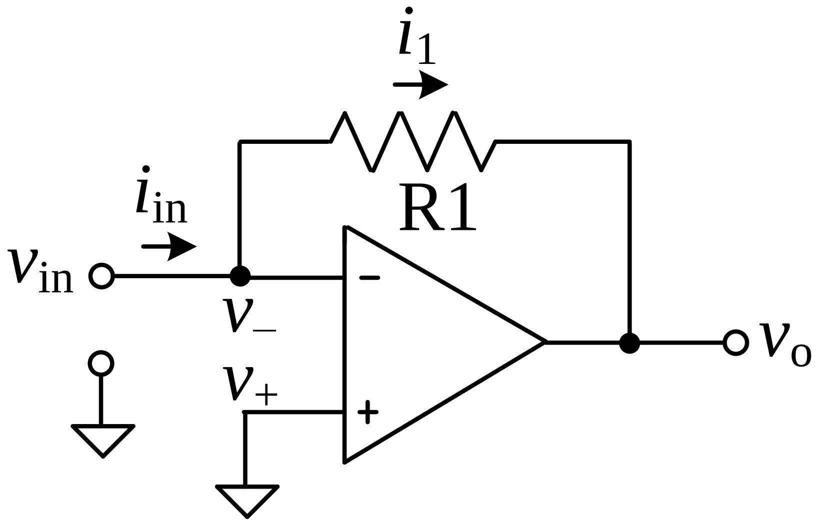
$R_{in1} = R_1 + R_2,\ R_{in2} = R_1 + R_2$,

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

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



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

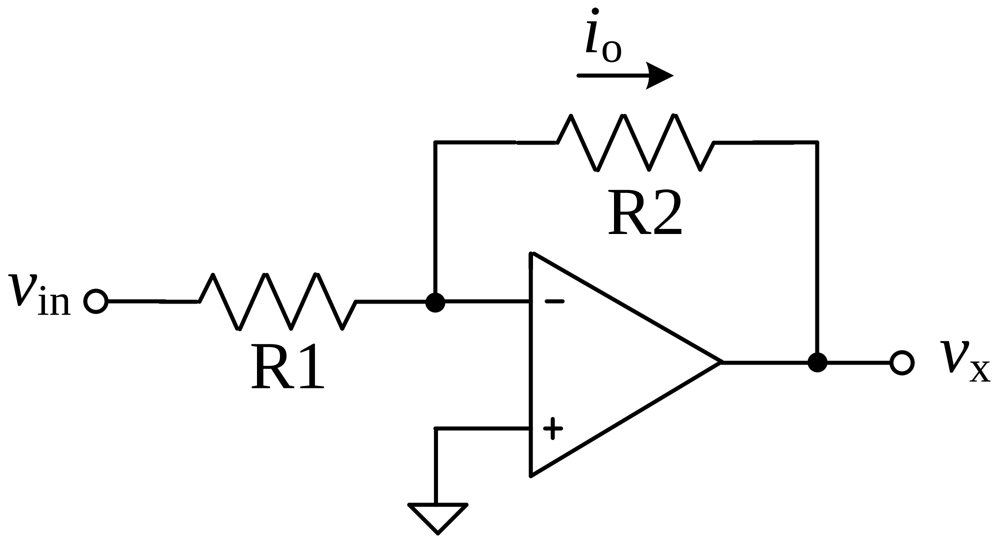
$R_{in} = 0$

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)

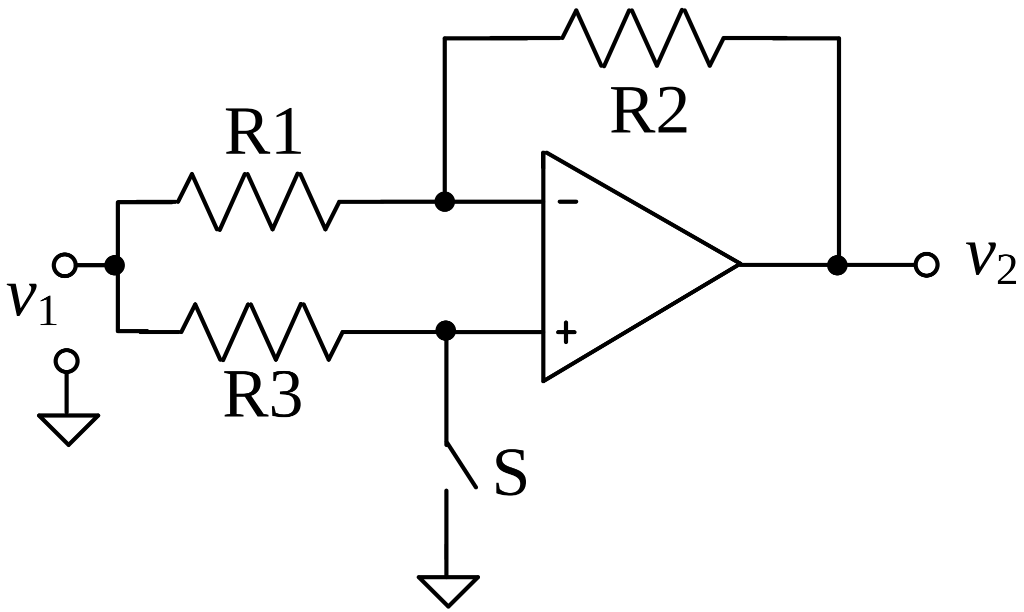
Re-purposed inverting amplifier circuit, for output current in load R2.

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



- **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 needed 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.**

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: $v_2 = (-R_2/R_1)\ v_1 + (1{+}R_2/R_1)\ v_1 = v_1$

$A = +1$

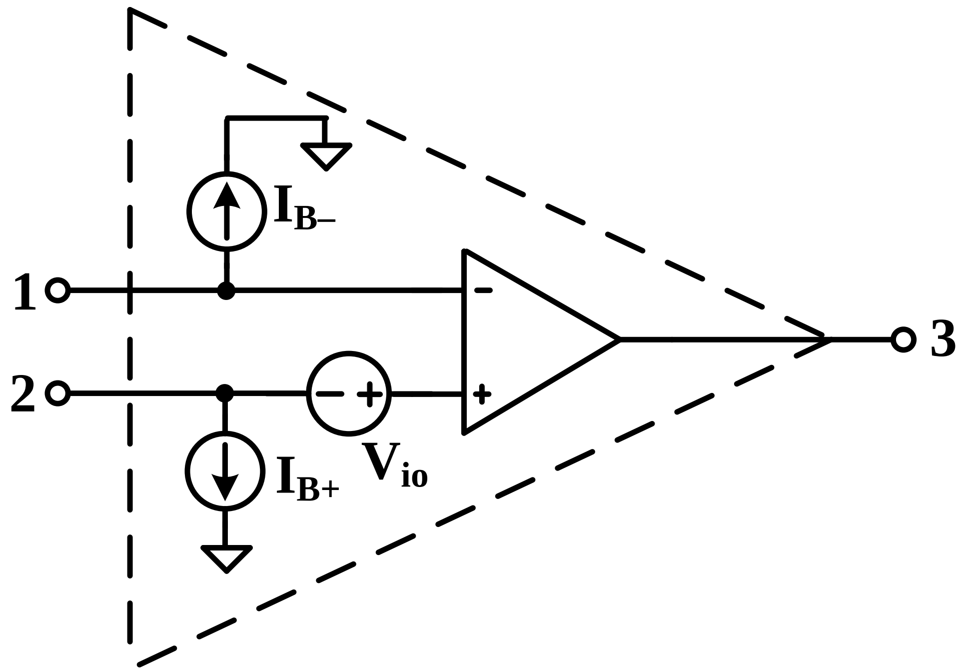
It is a simple example of 'programmable' or 'digitally-controlled' analog circuit.

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.



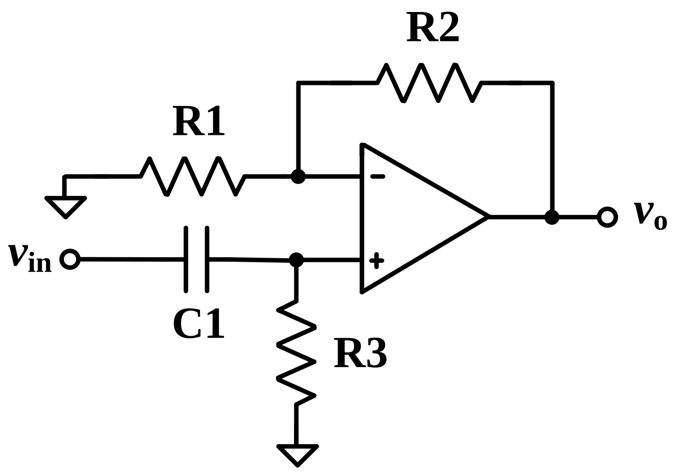
Op-amp DC error model

• 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

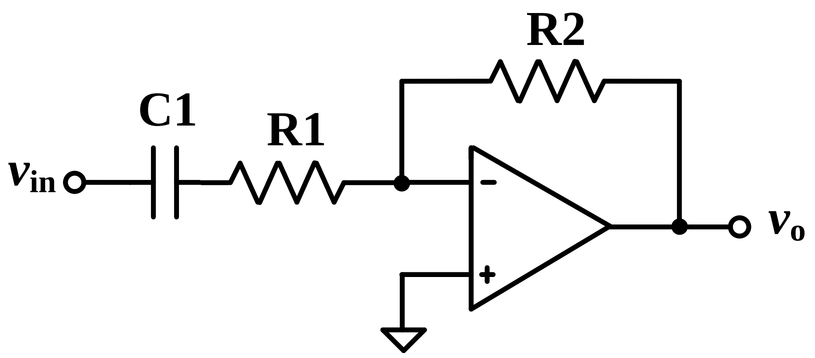
Amplification of a small time-varying (AC) component superimposed on a large constant (DC) component.
A capacitor is connected in series with the input to block the DC component & couple the AC component.
Capacitor impedance at the lowest frequency (f_{min}) << input resistance R_{in} & the circuit must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

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



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

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*

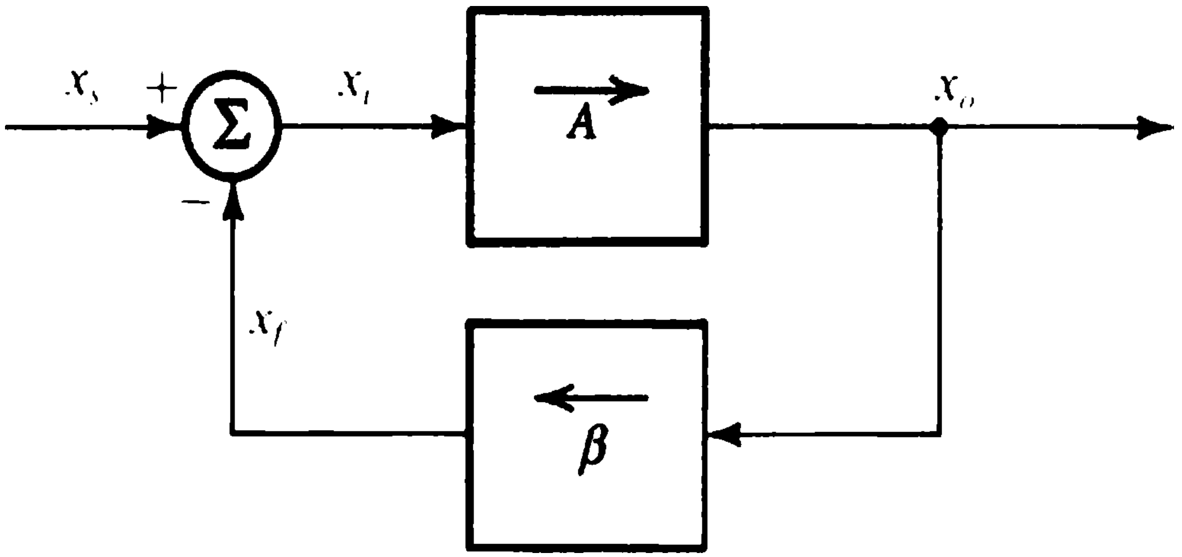
- Desensitize the gain, making it less sensitive to the circuit component parameters.
- Extend the bandwidth.
- Reduce nonlinear distortion.
- Reduce noise effects.
- Control the input and output resistances: raise or lower R_{in} and R_o by appropriate feedback topology.

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.

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).

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

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

- 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 $A\beta >> 1$.

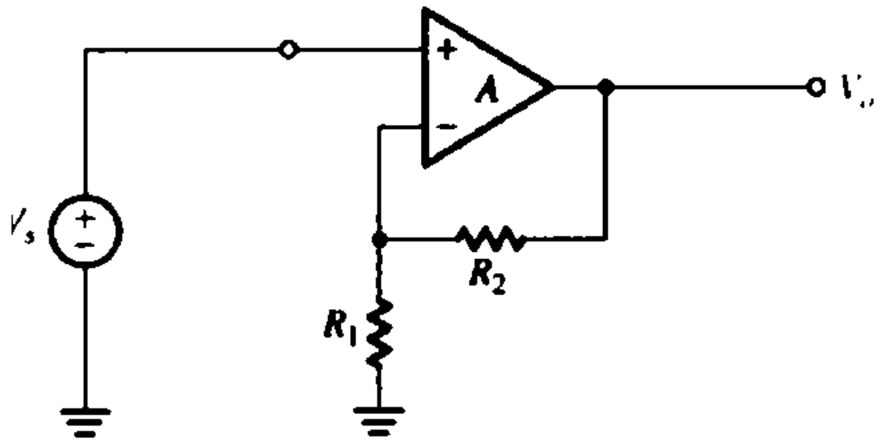
  Example: $A = 10^3$ to 10^5 & $\beta = 1/10$.

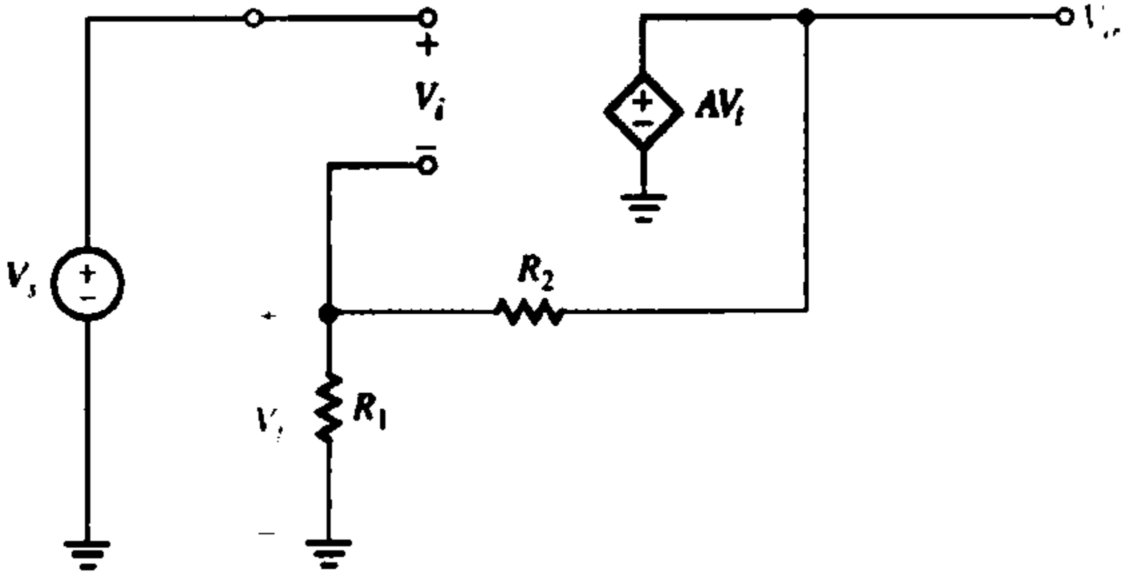
  (i) $A = 10^3 \Rightarrow A_f = 10/(1+10^{-2}) = 9.900$. (ii) $A = 10^5 \Rightarrow A_f = 10/(1+10^{-4}) = 9.9990$

- 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)





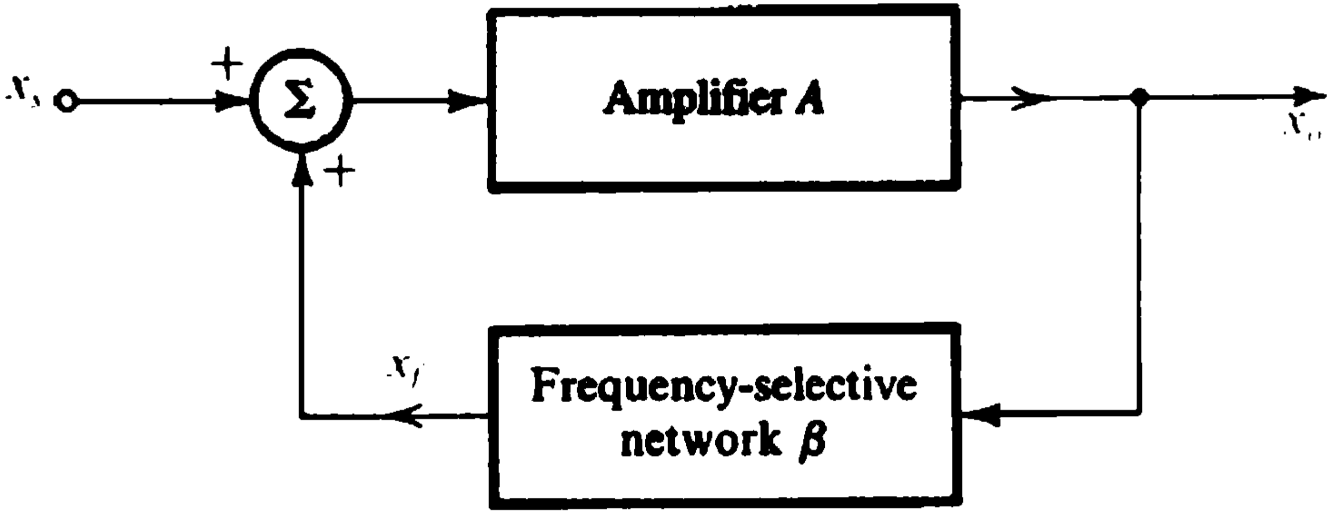
• Open-loop gain = op-amp differential gain. Feedback factor is set by resistive attenuator (R1, R2). Feedback subtraction is at the op-amp differential input.

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

• 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

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

$A\beta = 1 \quad \Rightarrow A_f = \infty \quad \Rightarrow$ 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).

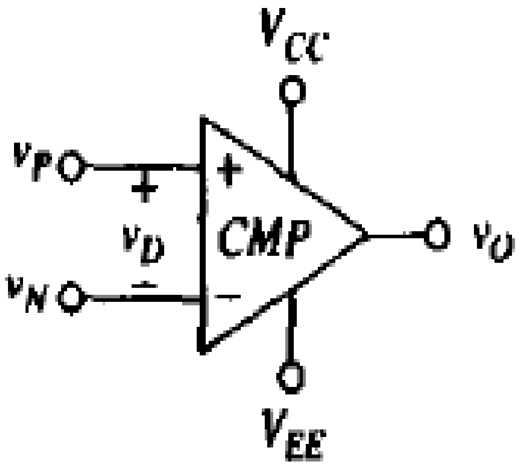
6. Nonlinear Circuits

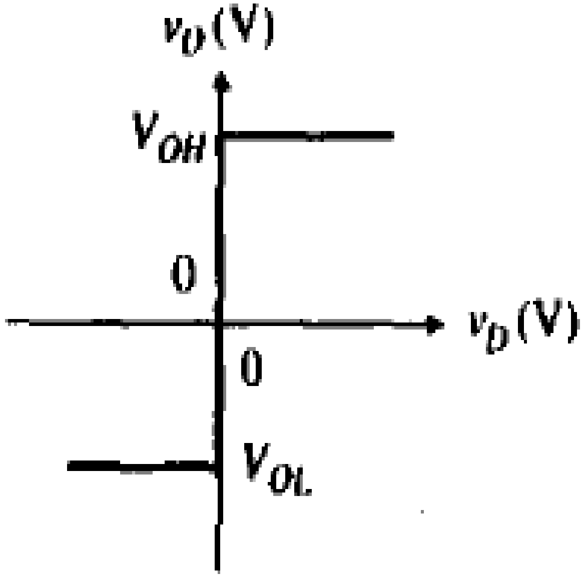
Voltage Comparator

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)





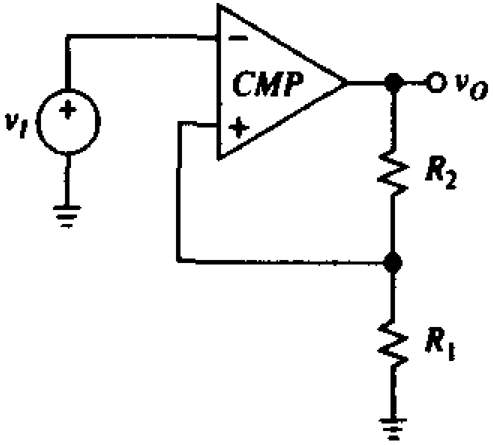
- Circuit symbol: same as op amp, with analog inputs, binary output. Transfer characteristic: Very high gain at $v_p = v_n$ with sharp transition between the two output levels.
- Input swing and output levels generally dependent on V_{CC+} and V_{EE-}.
- A comparator is designed for very low input currents 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.

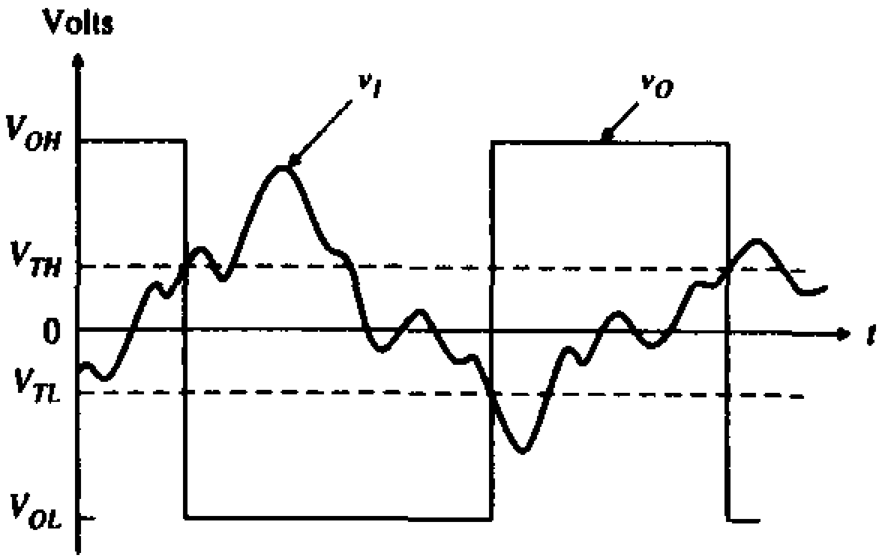
Schmitt Trigger

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

• Inverting Schmitt trigger: clockwise hysteresis.

• Non-inverting Schmitt trigger: counterclockwise hysteresis.





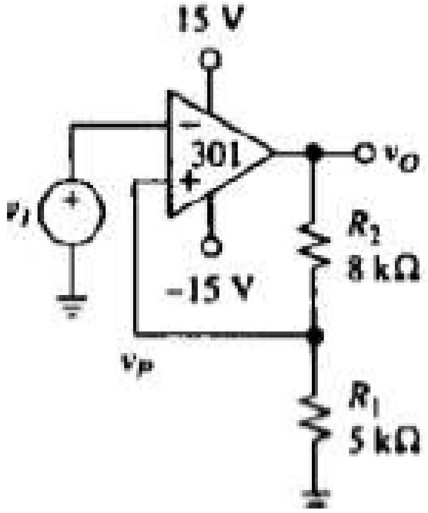
Applications: **Chatter elimination, waveform generation, signal processing.**

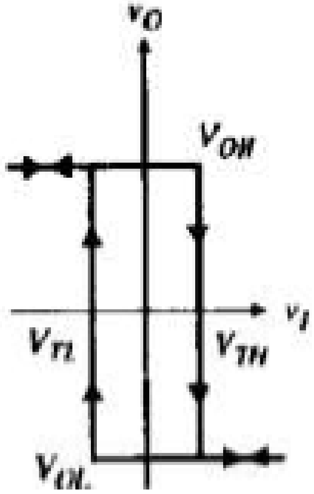
Inverting Schmitt trigger

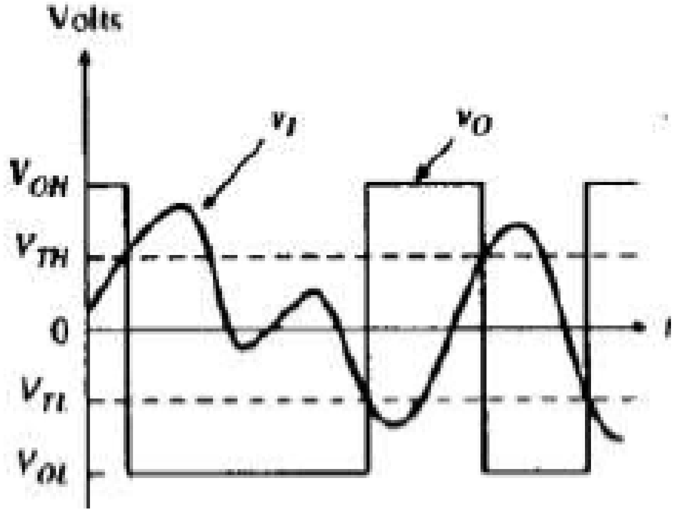
$$V_{TH} = \frac{R_1}{R_1 + R_2} V_{OH}$$

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

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





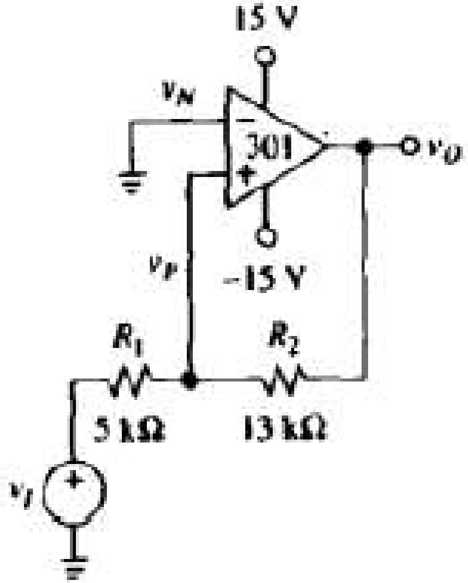


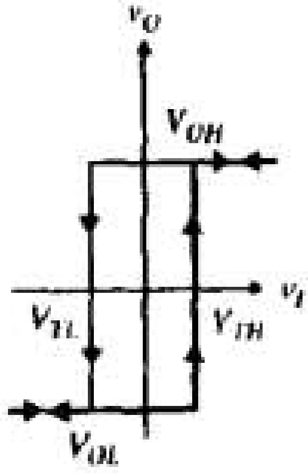
Noninverting Schmitt trigger

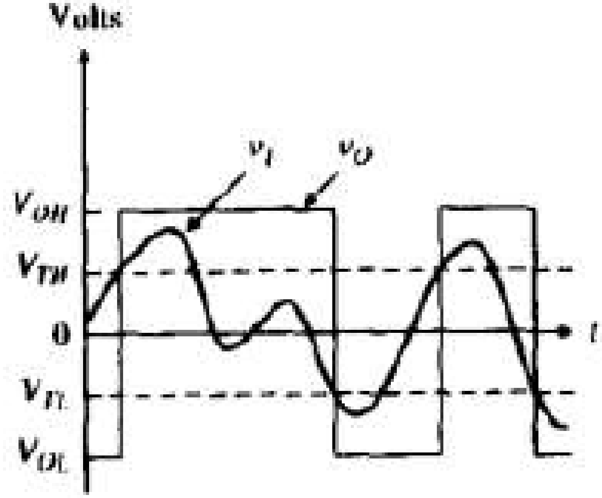
$$V_{TH} = -\frac{R_1}{R_2} V_{OL}$$

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

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







Thanks.