Operational Amplifier

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Unit 2

- **Op-Amp (operational amplifier):** Amplifier parameters, controlled source models, classification, the operational amplifier (OP-AMP) as a linear active device, the VCVS model of an op-amp, different amplifier configurations using op-amp (open loop-closed loop), frequency response of op-amp and op-amp based amplifiers. Calculation of CMRR, Gain Band width product. Op-Amp as integrator, differentiator, addition, subtraction etc.

Op-amp

- Direct coupled very high gain voltage amplifier
- Integrated circuit
- Differential input and single output

Direct coupled: the output of one stage of amplifier is connected directly to the input of next stage without any coupling capacitor

Ideal characteristics of op-amp

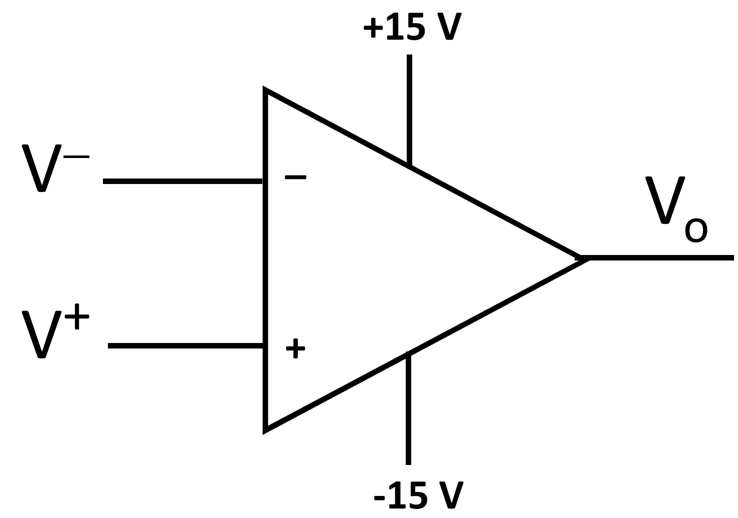
- Open loop gain infinite,

  $A_{OL} = \infty$
- Input impedance infinite,

  $R_i = \infty$
- Output impedance low,

  $R_o = 0$
- Bandwidth infinite,

  $BW = \infty$
- Zero offset, ie, $V_o = 0$ when $V^+ = V^- = 0$



Op-amp circuit symbol

Operational characteristics of op-amp

- Practical op-amp
  - Draws current
  - Inputs respond differently to currents and voltages due to mismatches in transistors
  - Operating point shifts with temperature
- Add error to the DC output voltage

DC non-ideal characteristics of op-amp

- Input bias current
- Input offset current
- Input offset voltage
- Thermal drift

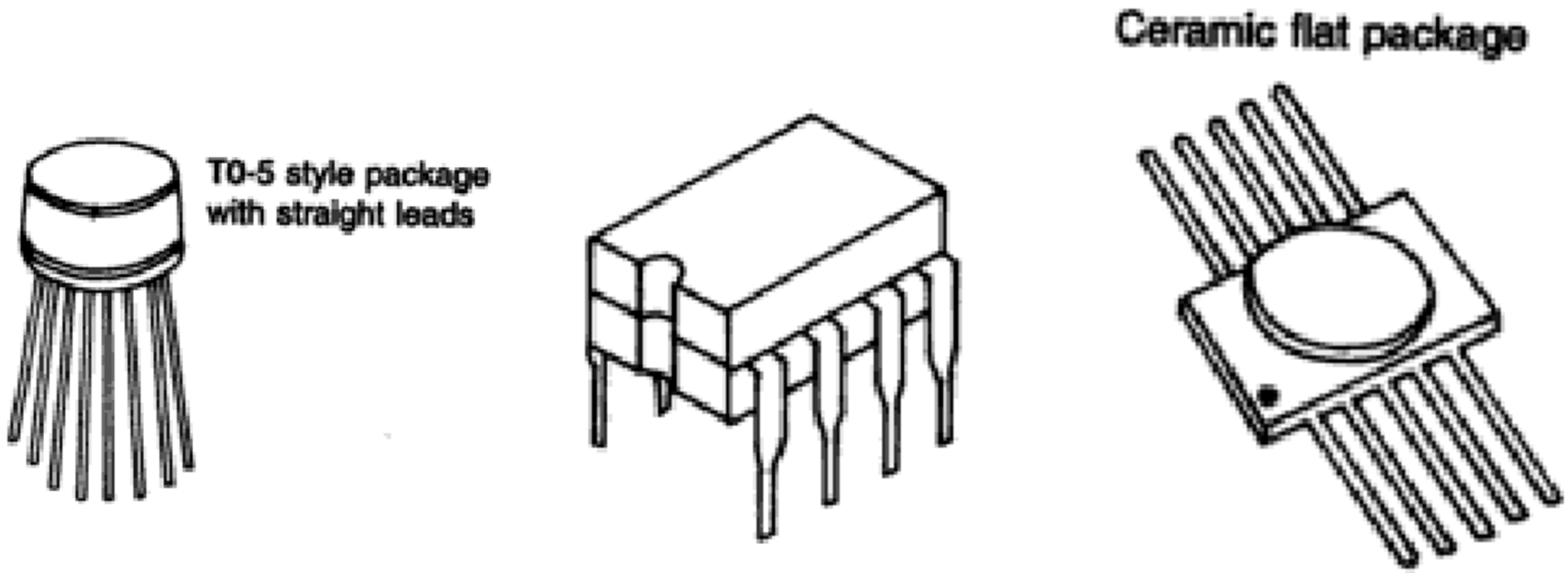
Differential and Common-Mode Signals

CMRR

- Common mode rejection ratio

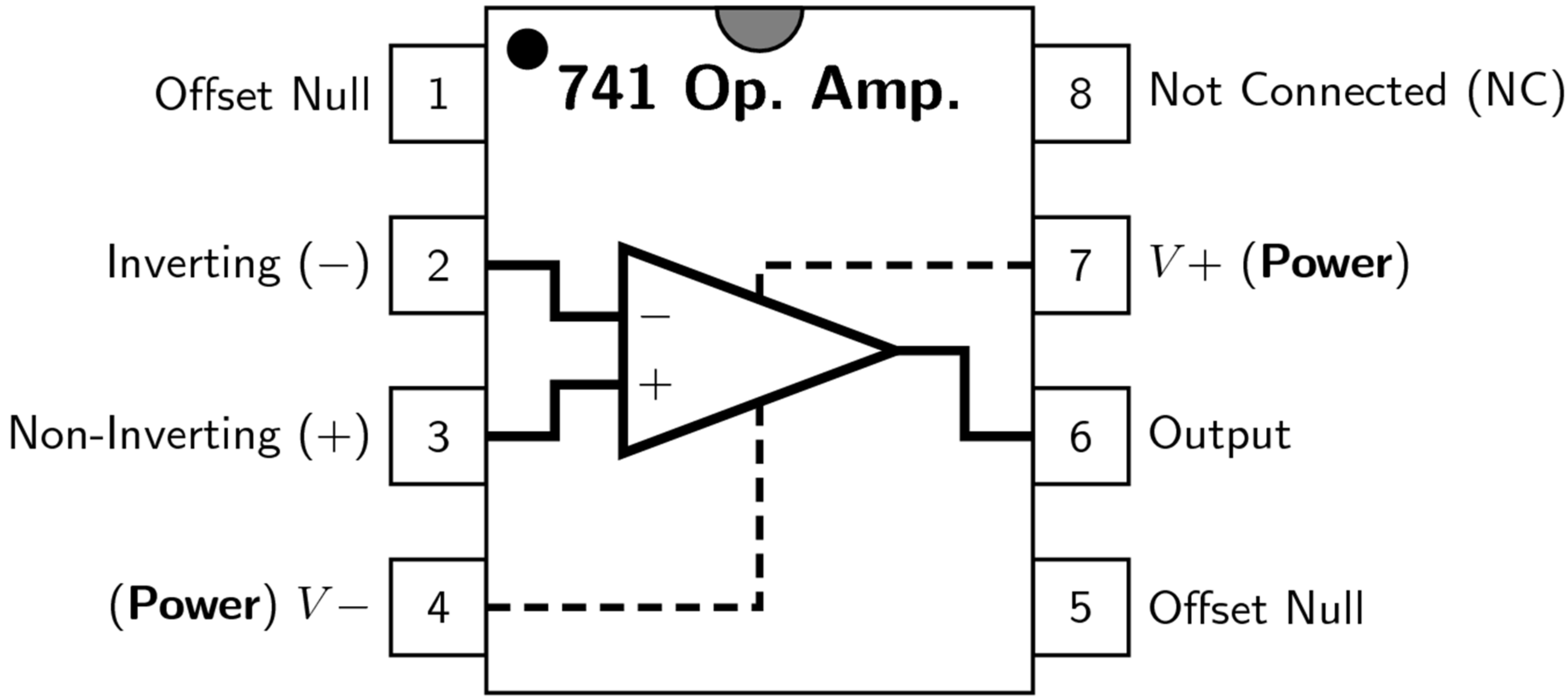
Packages of IC741

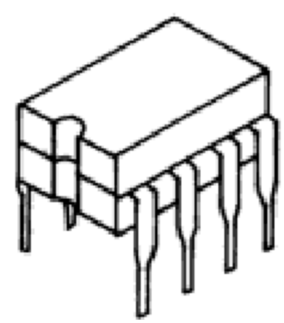
Metal can (TO) package, Dual-in-line package, Flat package



IC packages of $\mu A741$

Pin diagram of 741 op-amp

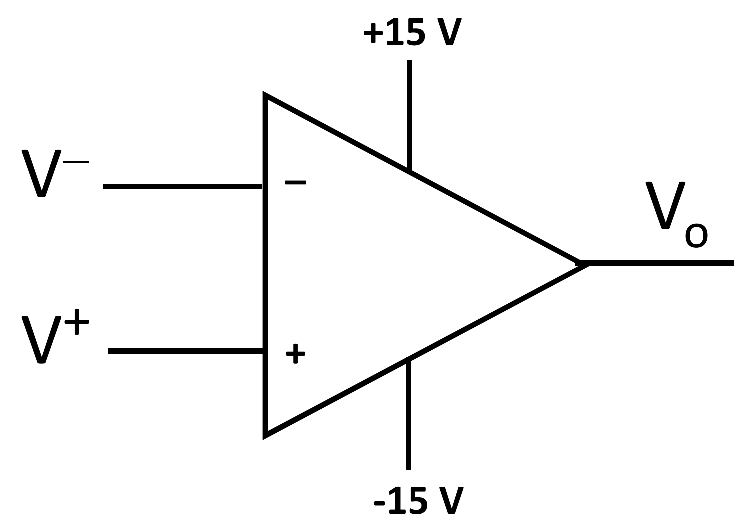




Dual-in-line package

Op-amp terminals

- Primarily
  - Two input terminals
    - Inverting terminal (V^-)
    - Non-inverting terminal (V^+)
  - One output terminal
  - Two terminals for power supply



Op-amp circuit symbol

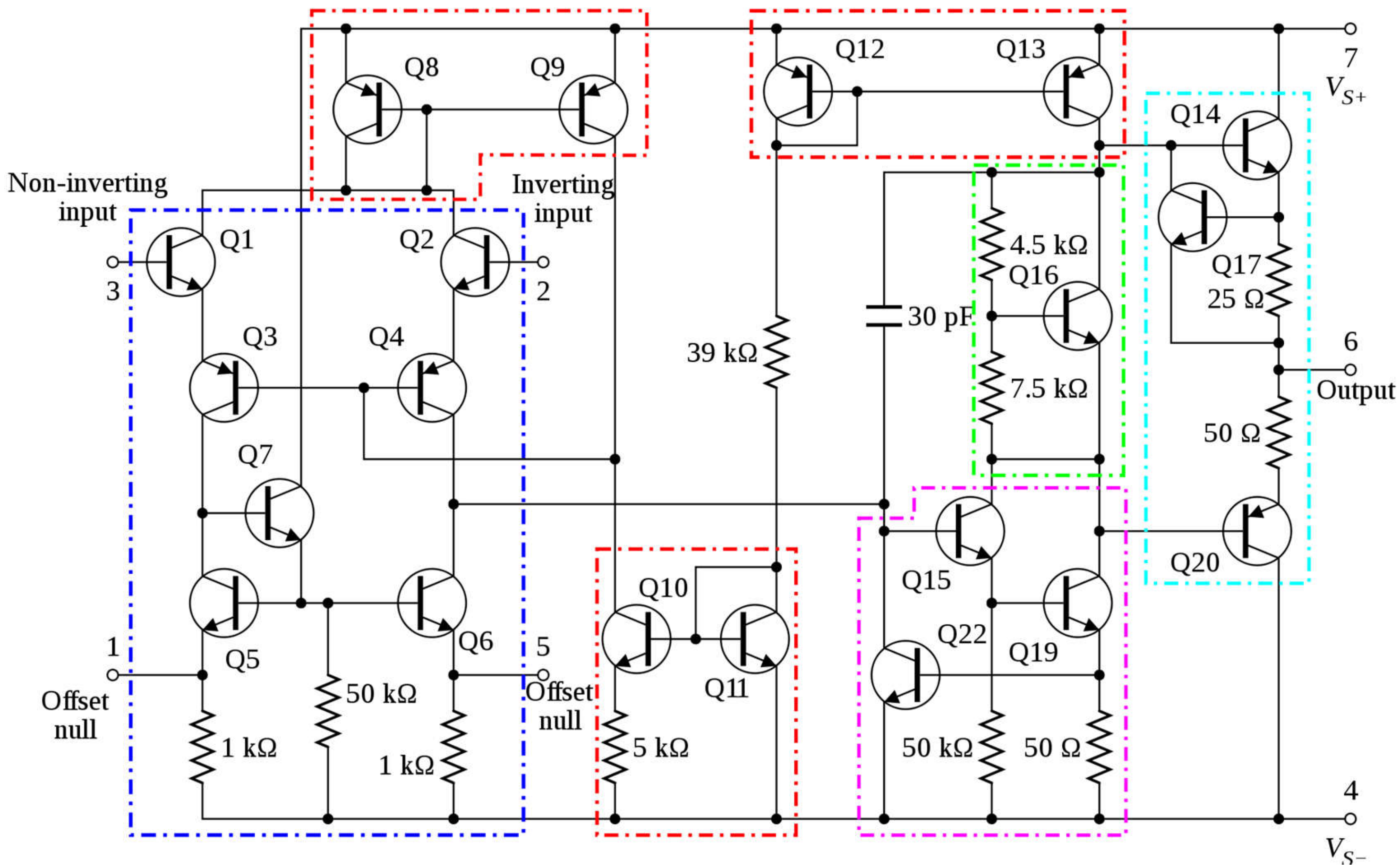
Op-amp manufacturers

Manufacturer	Product number
Fairchild (Original)	μA741
National semiconductor	LM741
Motorola	MC1741
RCA	CA3741
Texas instruments	SN52741
Signetics	N5741

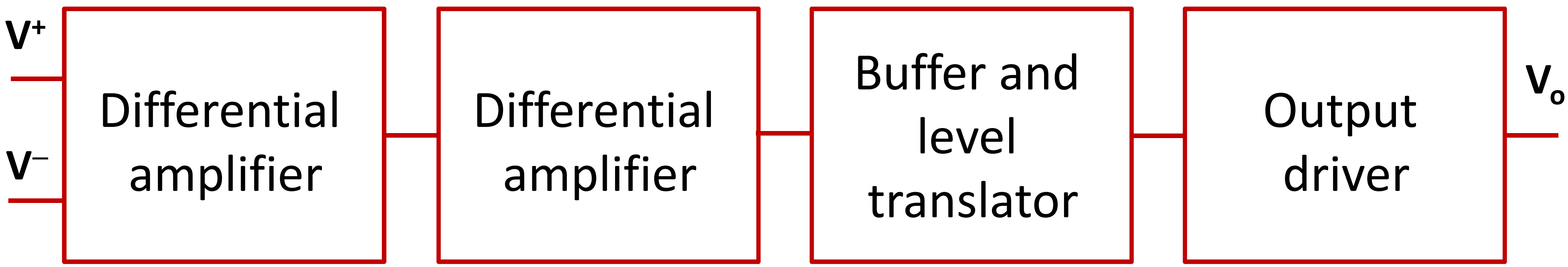
Op-amp classes

<table>
<tr><th>Class</th><th colspan="2">Application</th></tr>
<tr><td>741</td><td colspan="2">Military grade op-amp
(Operating temp. range -55 ^oC to 125 ^oC)</td></tr>
<tr><td>741C</td><td colspan="2">Commercial grade op-amp
(Operating temp. range 0 ^oC to 70/75 ^oC)</td></tr>
<tr><td>741A</td><td>Improved version of 741</td><td rowspan="2">Better electrical specifications</td></tr>
<tr><td>741E</td><td>Improved version of 741 C</td></tr>
<tr><td>741S</td><td colspan="2">Military grade op-amp with higher slew-rate</td></tr>
<tr><td>741SC</td><td colspan="2">Commercial grade op-amp with higher slew-rate</td></tr>
</table>

Internal circuit diagram of 741

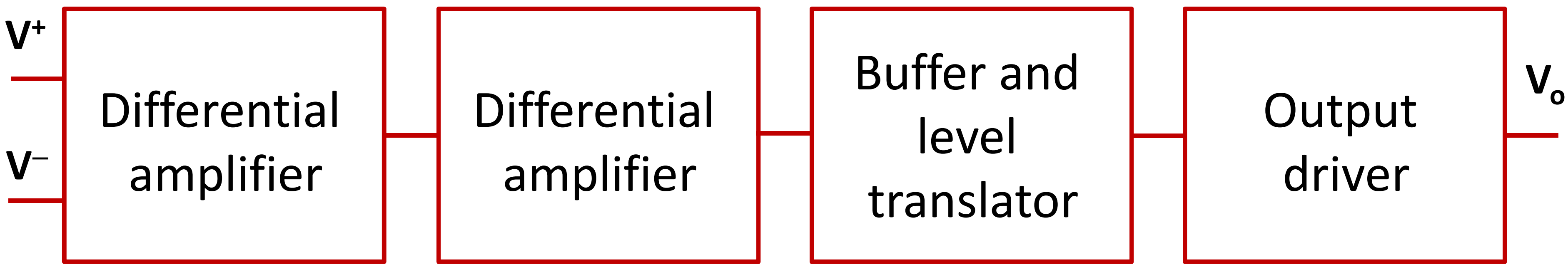


Block diagram of op-amp



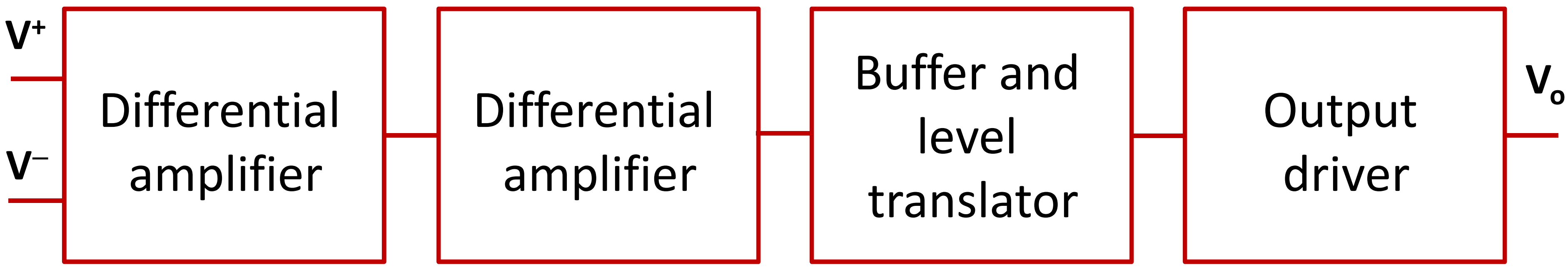
- First two stages, cascaded differential amplifier
  - High gain, high resistance

Block diagram of op-amp



- Buffer
  - Emitter follower
  - Very high input impedance, to prevent loading to the amplifier
- Level shifter
  - Adjusts DC voltages so that output voltage is zero for zero input voltage

Block diagram of op-amp

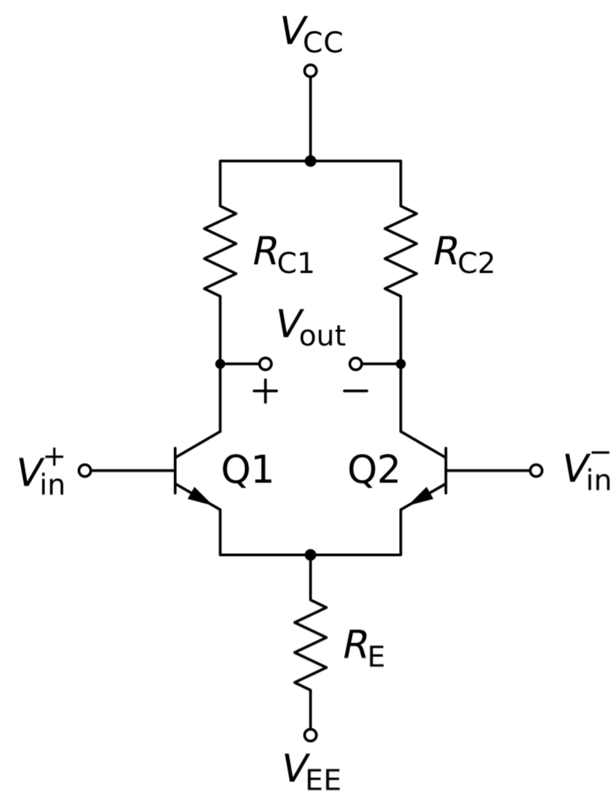


- Output stage
  - To provide low output impedance

Differential amplifier

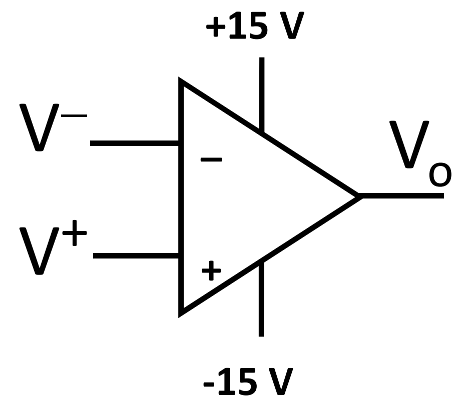
- Provide high gain to the difference-mode signal
- Cancel common-mode signal

Block diagram of op-amp

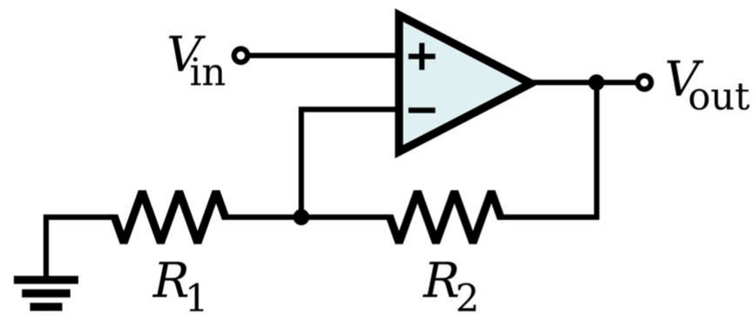


Operations of op-amp

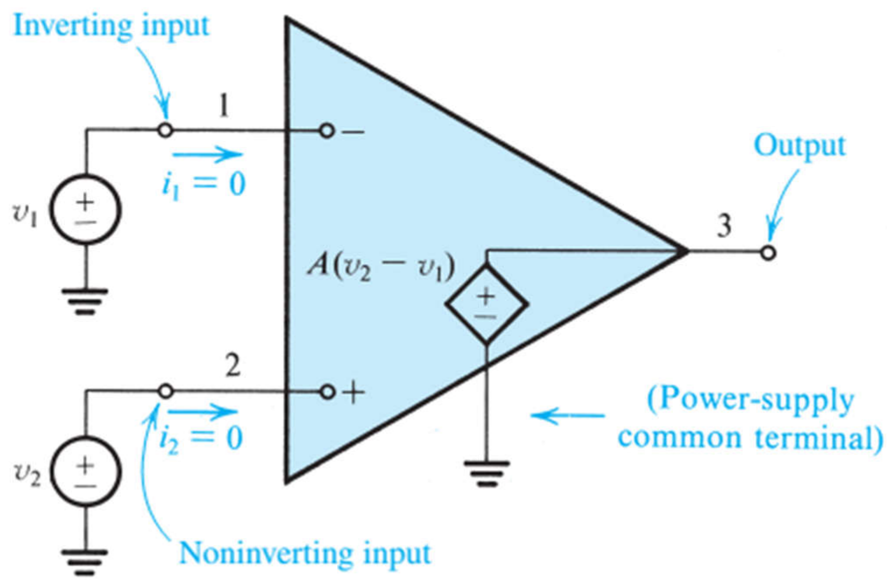
- **Open loop**
  - Output is driven into saturation
  - Comparator
  - Zero crossing detector



- **Closed loop**
  - Negative feed back
  - Linear output range

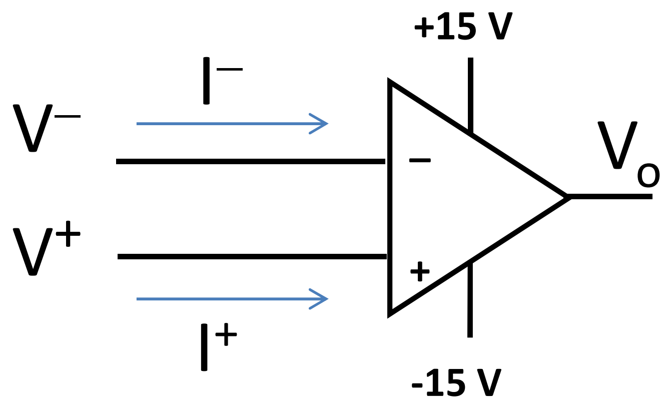


Equivalent circuit of the ideal op-amp (VCVS model of op-amp)



Analysis of op-amp

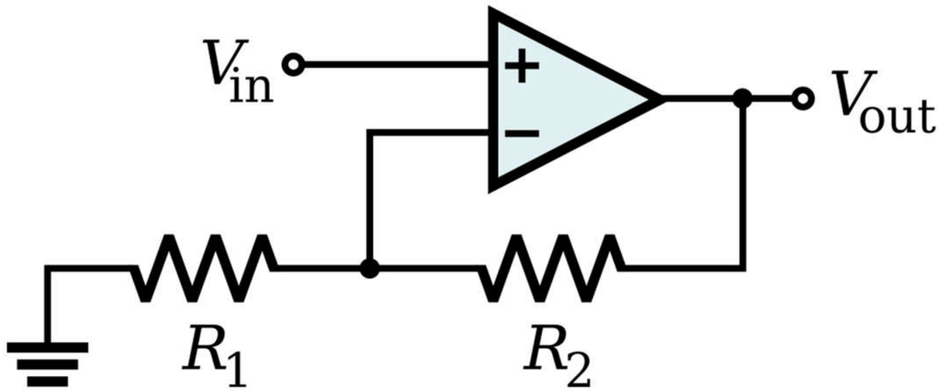
- Assumptions
  - Current entering the op-amp terminals is zero, $\mathbf{I^+ = I^- = 0}$
  - Difference voltage is zero, $\mathbf{V^+ - V^- = 0}$



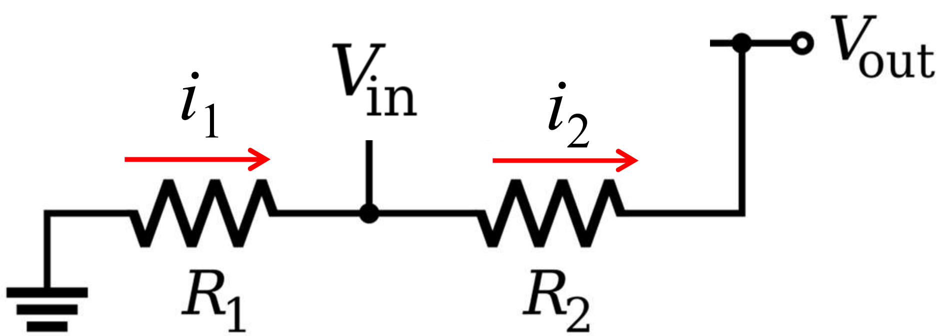
Non-inverting op-amp

$$i_1 = i_2$$

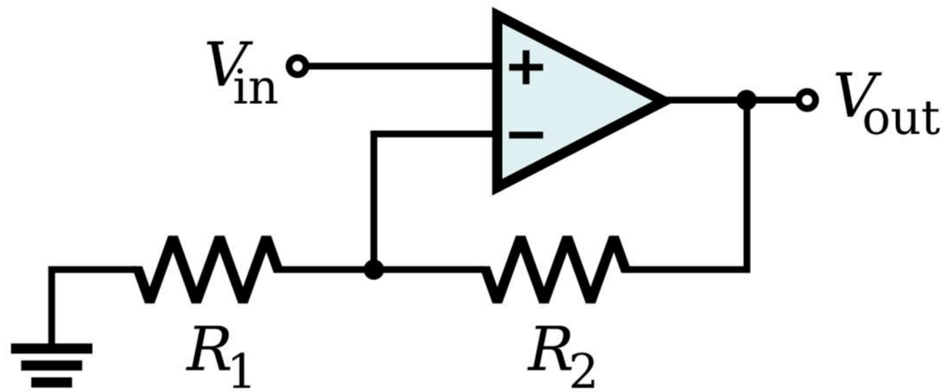
$$\frac{0 - V_{in}}{R_1} = \frac{V_{in} - V_{out}}{R_2}$$



$$V_{out} = \left(1 + \frac{R_2}{R_1}\right) V_{in}$$

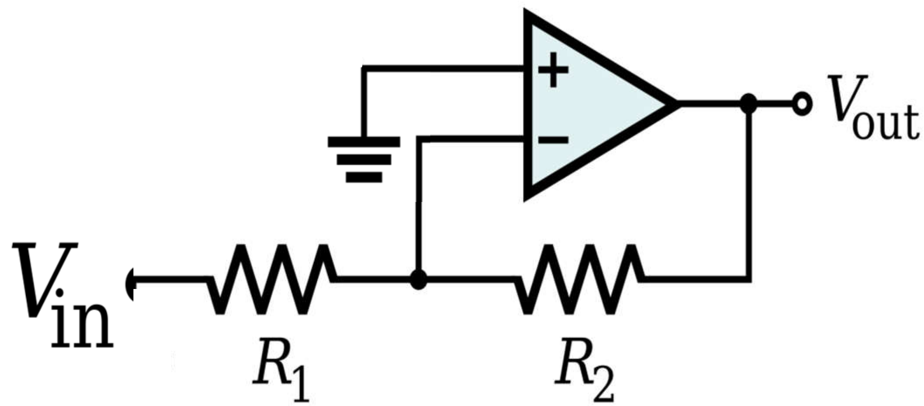


Q: why do you require R_1

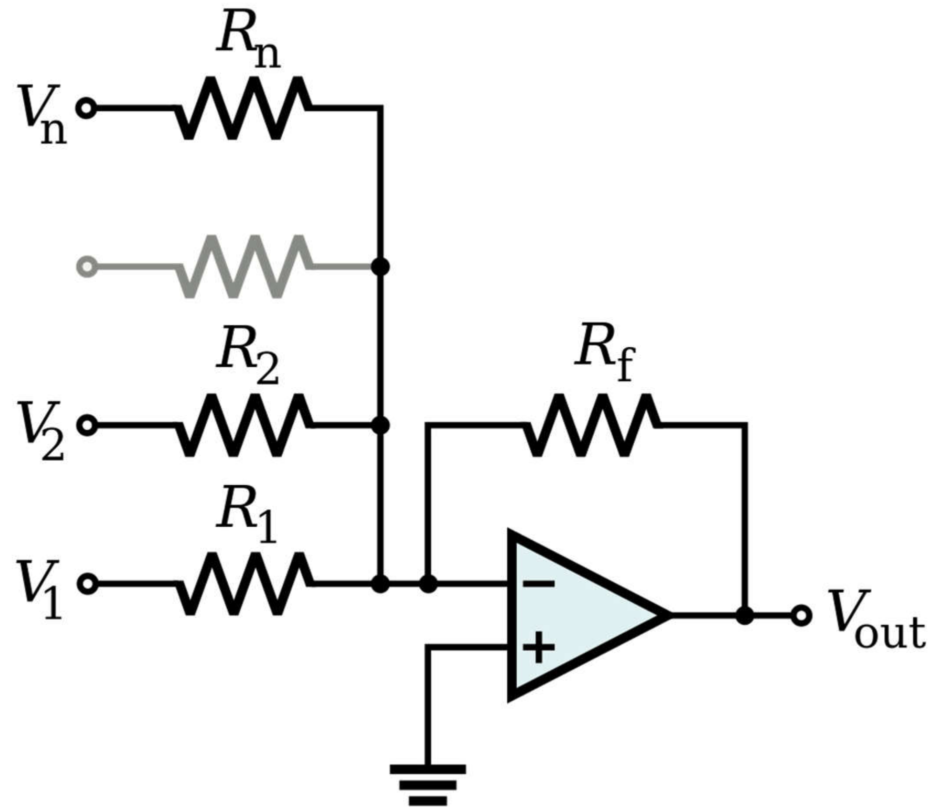


Inverting op-amp

$$V_{out} = -\frac{R_2}{R_1} V_{in}$$

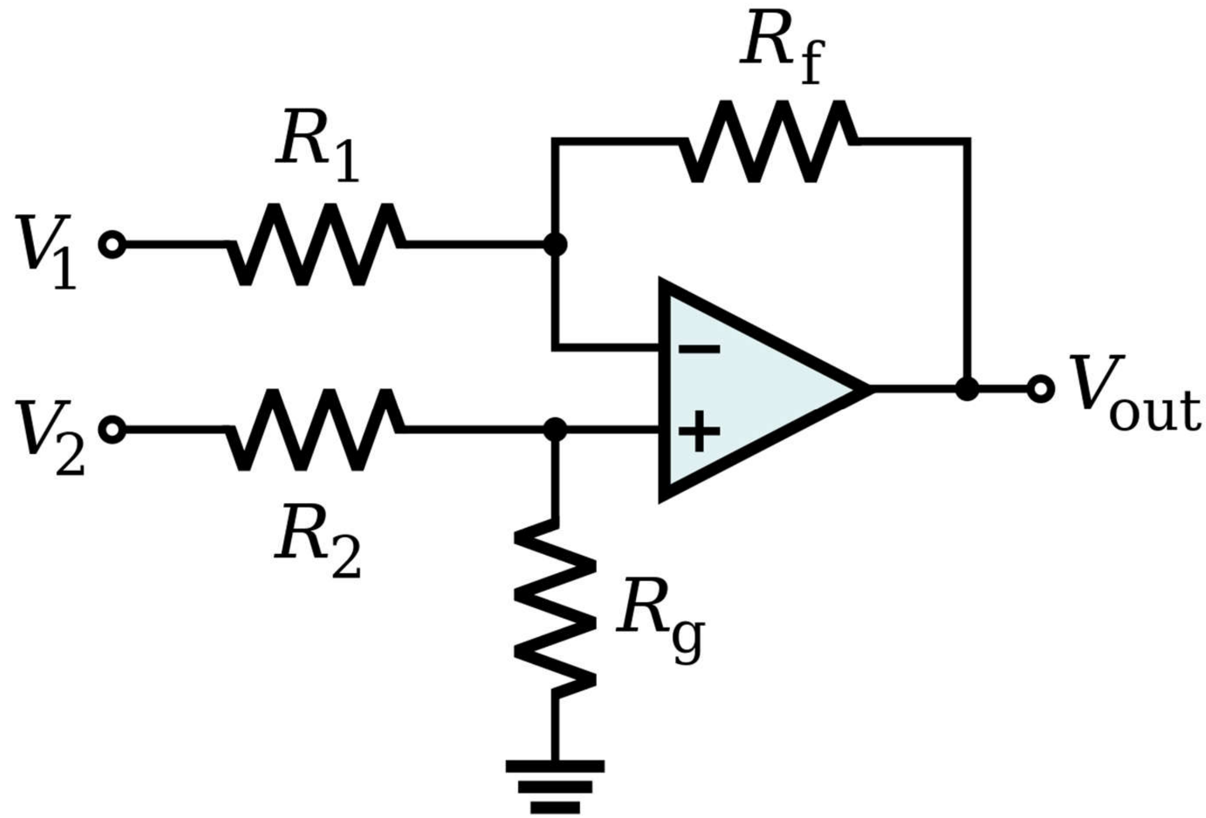


Inverting summing amplifier

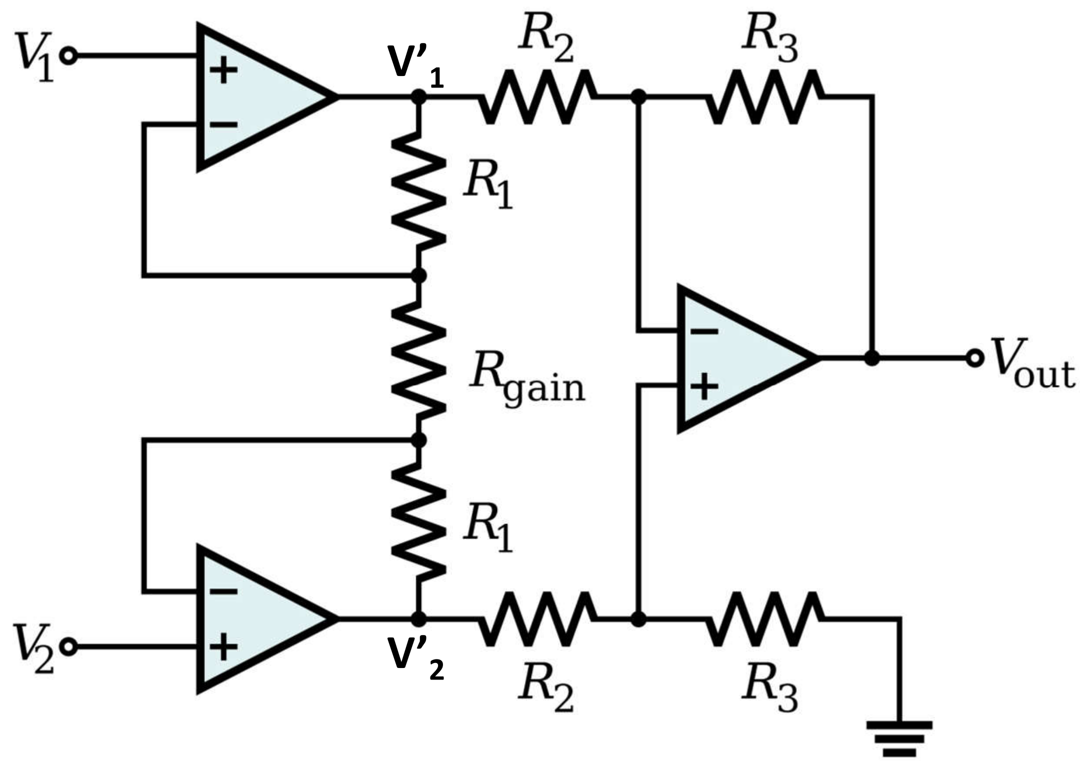


$$V_{out} = -\left(\frac{R_f}{R_1} + \frac{R_f}{R_2} + \ldots\ldots\ldots\ldots + \frac{R_f}{R_n}\right)V_{in}$$

Difference amplifier



Instrumentation amplifier

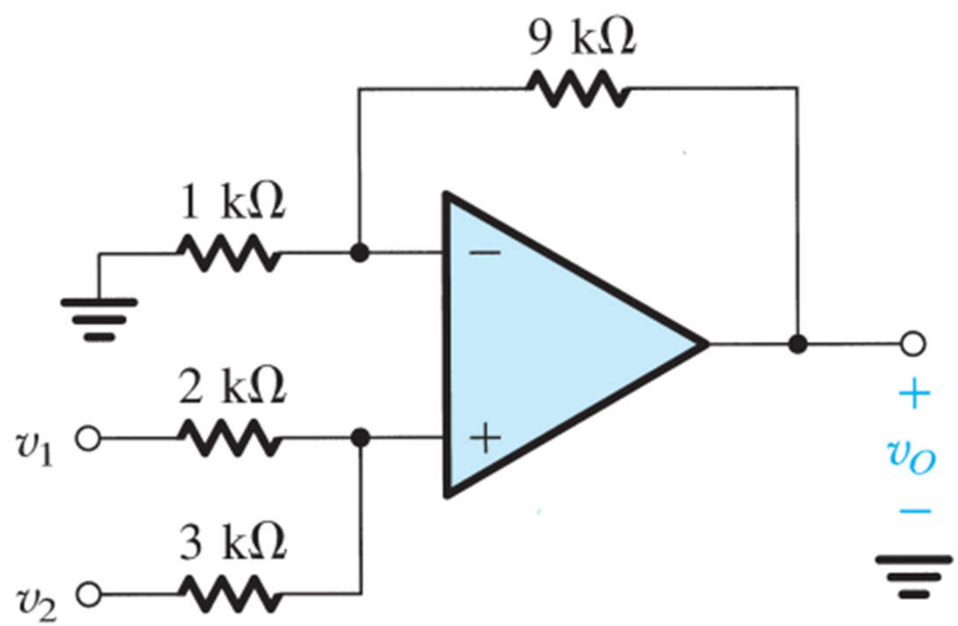


$$V_{out} = \left(1 + \frac{2R_1}{R_{gain}}\right)\left(\frac{R_3}{R_2}\right)[V_2 - V_1]$$

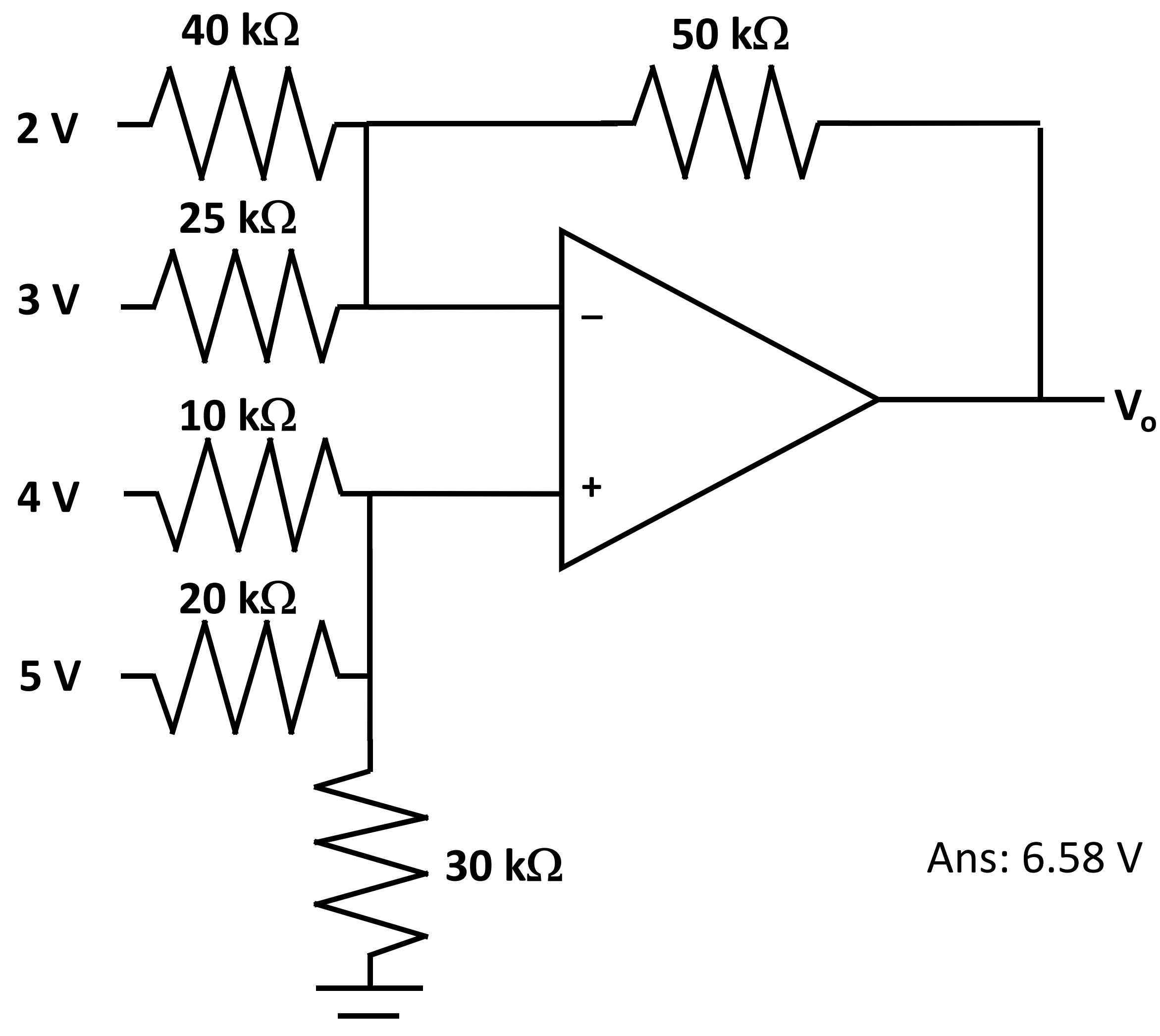
Problem: Superposition theorem

- Use the superposition principle to find the output voltage of the circuit shown in Fig.

$$v_O = 6v_1 + 4v_2$$

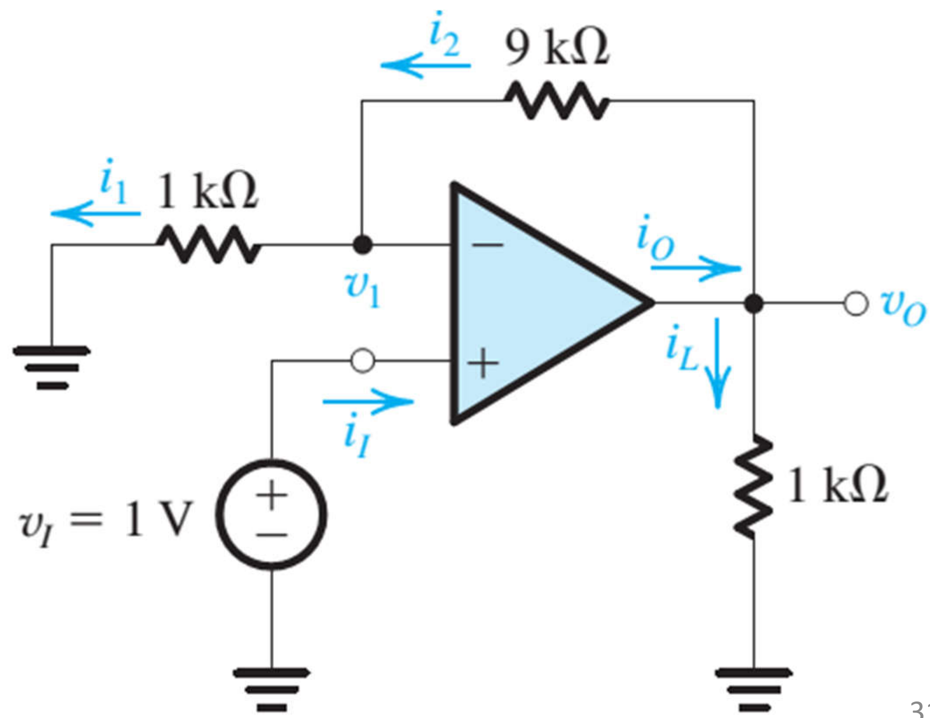


Problem: find V_o



Ans: 6.58 V

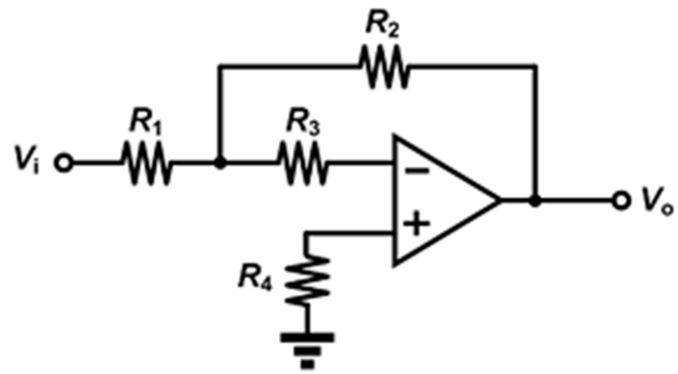
- For the circuit in Fig. find the values of i_I, v_1, i_1, i_2, v_o, i_L, and i_o. Also find the voltage gain v_o/v_I, the current gain i_L/i_I, and the power gain P_L/P_I



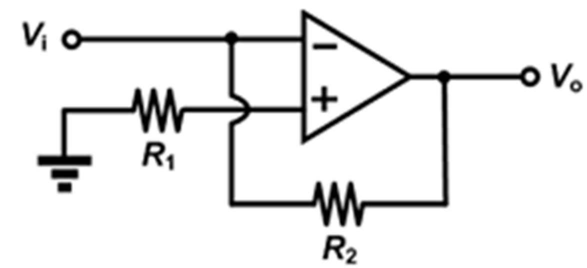
0; 1 V; 1 mA; 1 mA; 10 V; 10 mA; 11 mA; 10 V/V (20 dB);∞;∞

Assignment B.1

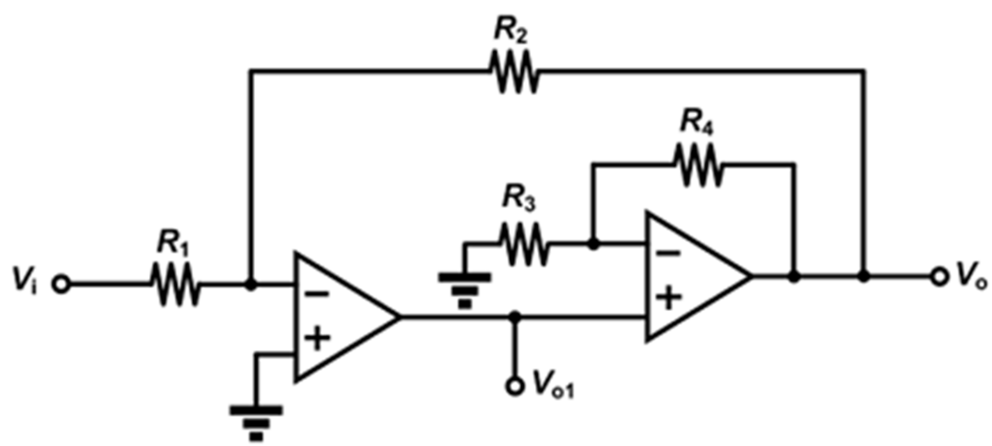
(1)



(2)

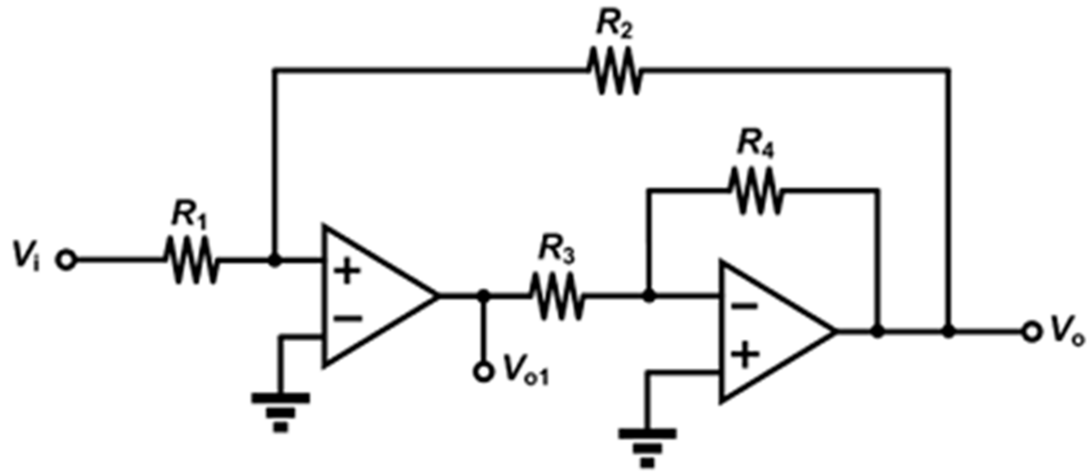


(3)



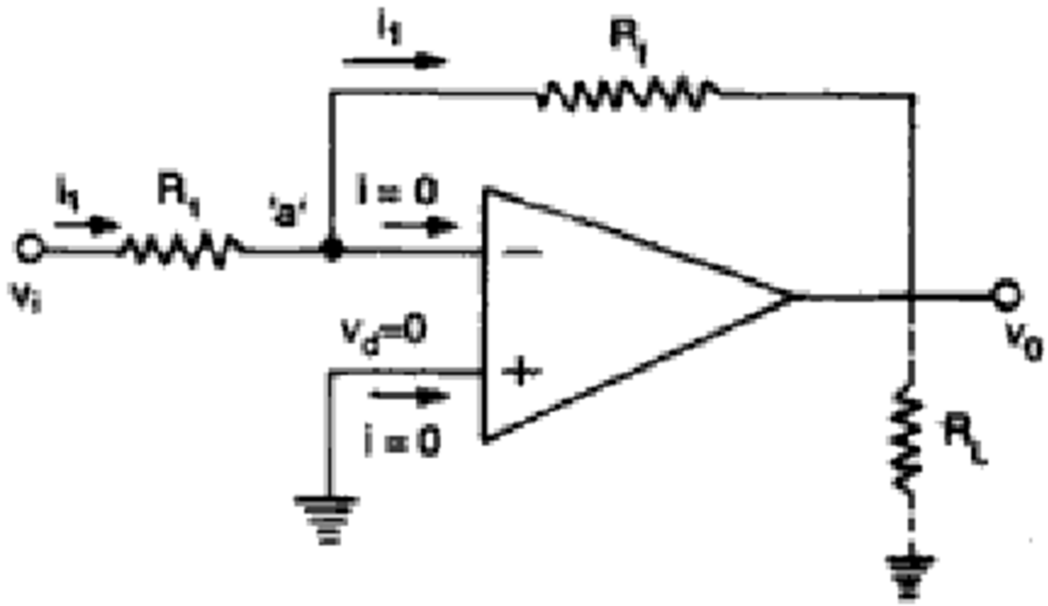
Assignment B.1

(4)



Assignment B.2

- R_1 = 10 kΩ, R_f = 100 kΩ, v_i = 1 V. A load of 25 kΩ is connected to the output terminal. Calculate (1) i_1 (2) v_o (3) i_L and (4) total current i_o into the output pin.

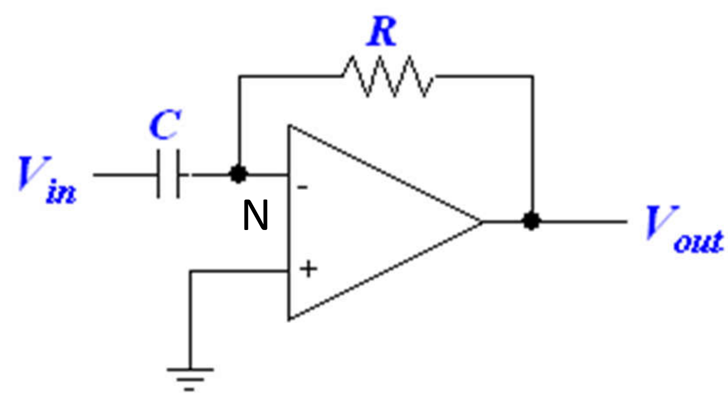


Differentiator

Current flowing through capacitor

$$i_C = C\frac{d}{dt}(v_i - v_N) = C\frac{dv_i}{dt}$$

Nodal equation at N



$$C\frac{dv_i}{dt} + \frac{v_o}{R_F} = 0$$

Solving

$$v_o = -R_F C\frac{dv_i}{dt}$$

Integrator

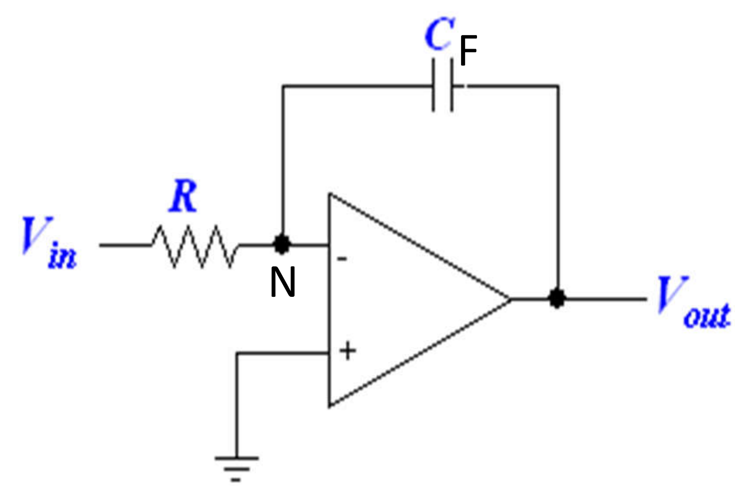
Nodal equation at N

$$\frac{v_i}{R_1} + C_F \frac{dv_o}{dt} = 0$$

$$\frac{dv_o}{dt} = -\frac{1}{R_1 C_F} v_i$$

Integrating on both sides

$$v_o = -\frac{1}{R_1 C_F} \int_0^t v_i(t)\, dt$$



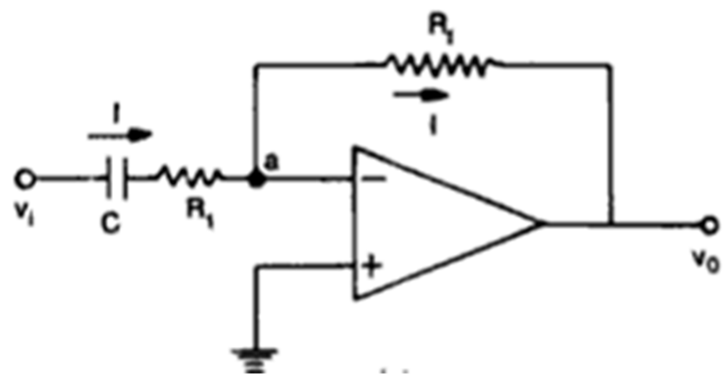
AC amplifier

- Inverting
- Non-inverting
- To get frequency response

$$V_o = -IR_f = \frac{V_i}{R_1 + \frac{1}{sC}} R_f$$

$$A_{CL} = \frac{V_o}{V_i} = -\frac{R_f}{R_1} \frac{s}{s + \frac{1}{R_1 C}}$$

$$s = j\omega$$



Voltage to current converter Transconductance amplifier

- Floating load
- Grounded load

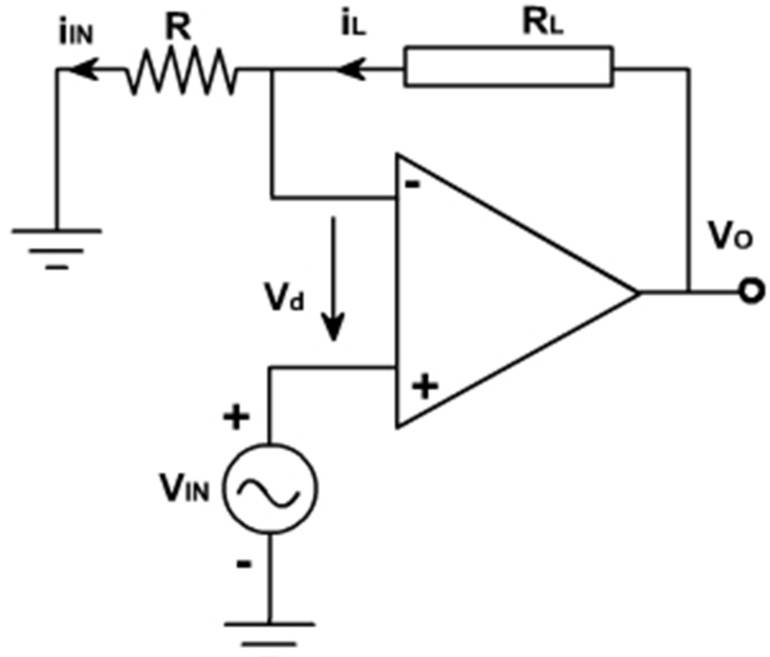
Voltage to current converter Transconductance amplifier

- Floating load

$$V_{IN} = i_{IN} R$$

$$i_{IN} = \frac{V_{IN}}{R}$$

$$i_L = i_{IN} = \frac{V_{IN}}{R}$$

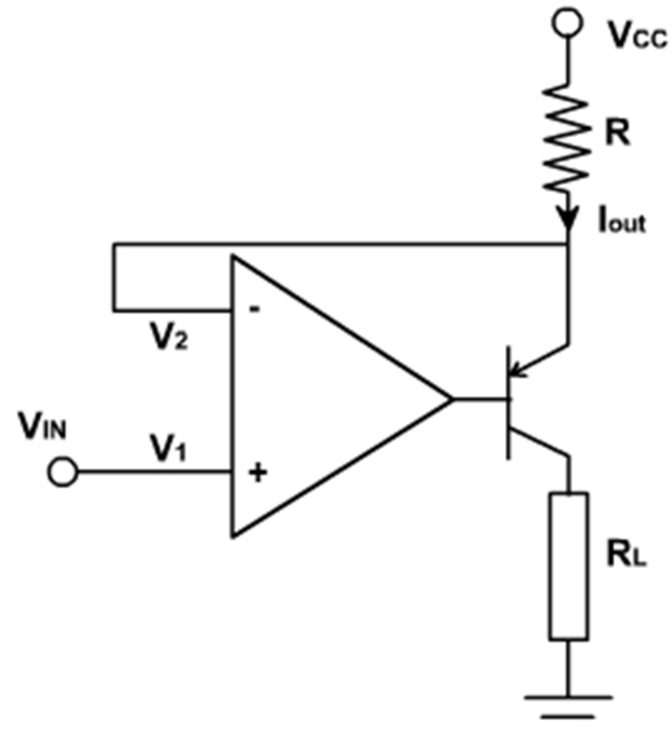


Voltage to current converter Transconductance amplifier

- Grounded load

$$V_2 = V_{IN}$$

$$I_{OUT} = \frac{V_{CC} - V_{IN}}{R}$$



Voltage to current converter Transconductance amplifier

- Grounded load

$$i_1 + i_2 = i_L$$

$$\frac{v_i - v_1}{R} + \frac{v_o - v_1}{R} = i_L$$

$$v_1 = \frac{v_i + v_o - i_L R}{2} \qquad (1)$$

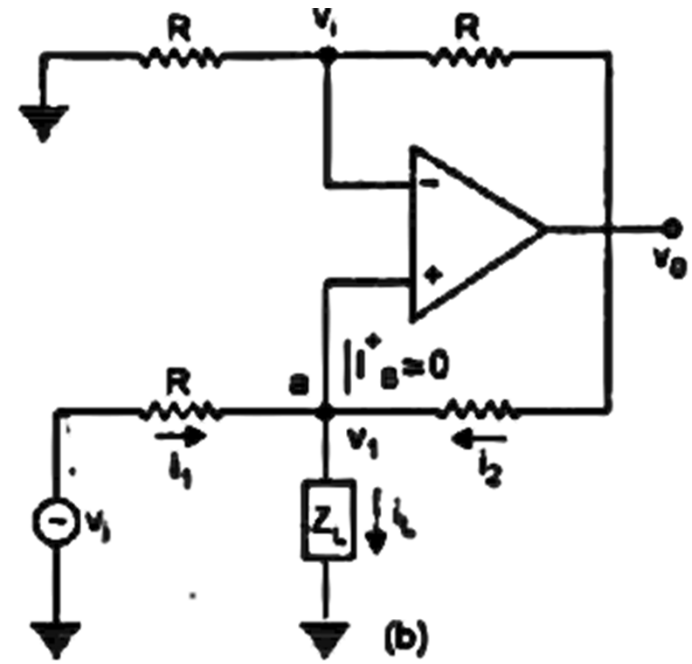
$$Non - inverting\ op - amp$$

$$v_o = \left[1 + \frac{R}{R}\right] v_1 = 2v_1 \qquad (2)$$

$$From\ Eqns.(1)\ \&\ (2)$$

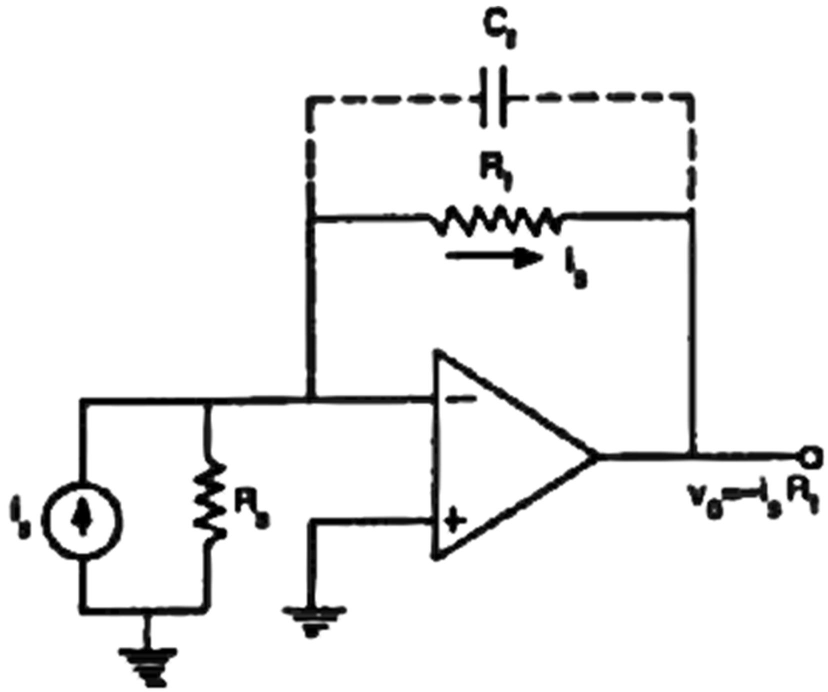
$$v_i - i_L R = 0$$

$$i_L = \frac{v_i}{R}$$



Current to voltage converter (Transresistance amplifier)

- The output current (proportional to incident radiant energy or light) of a photocell, photodiode and photovoltaic cell can be converted into voltage
- Capacitor serves as filter

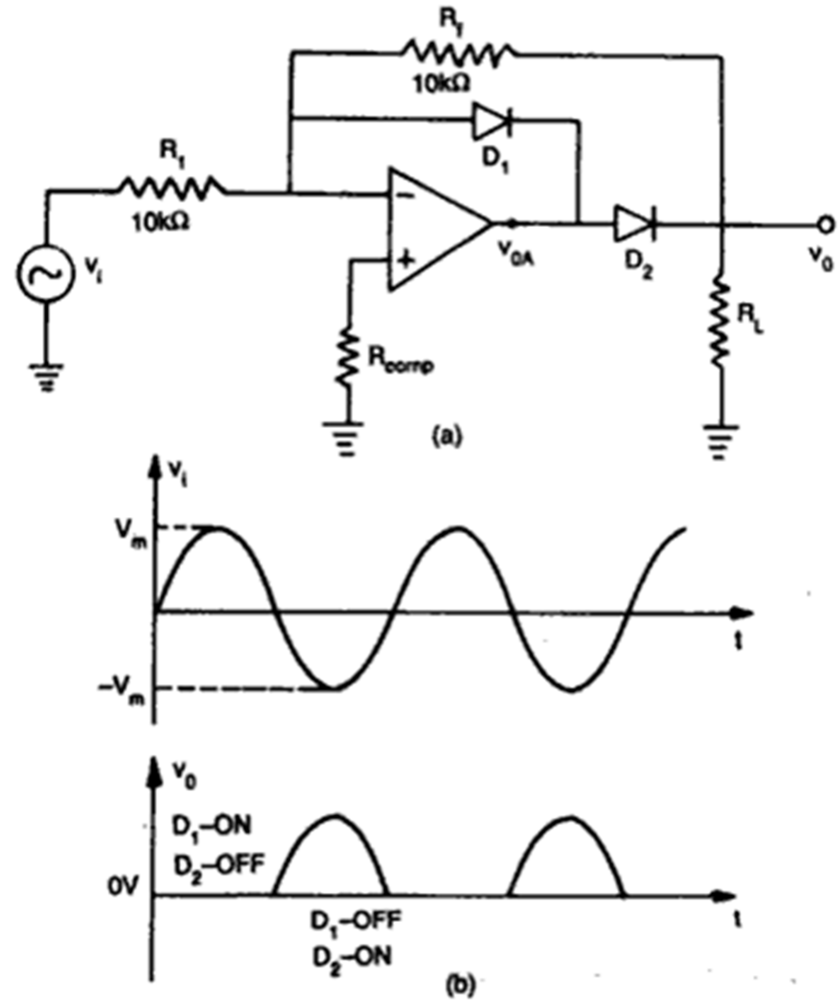


$$v_o = -i_s R_f$$

Op-amp circuits using diodes

- Half-wave rectifier
- Full-wave rectifier
- Peak-value detector
- Clipper
- Clamper

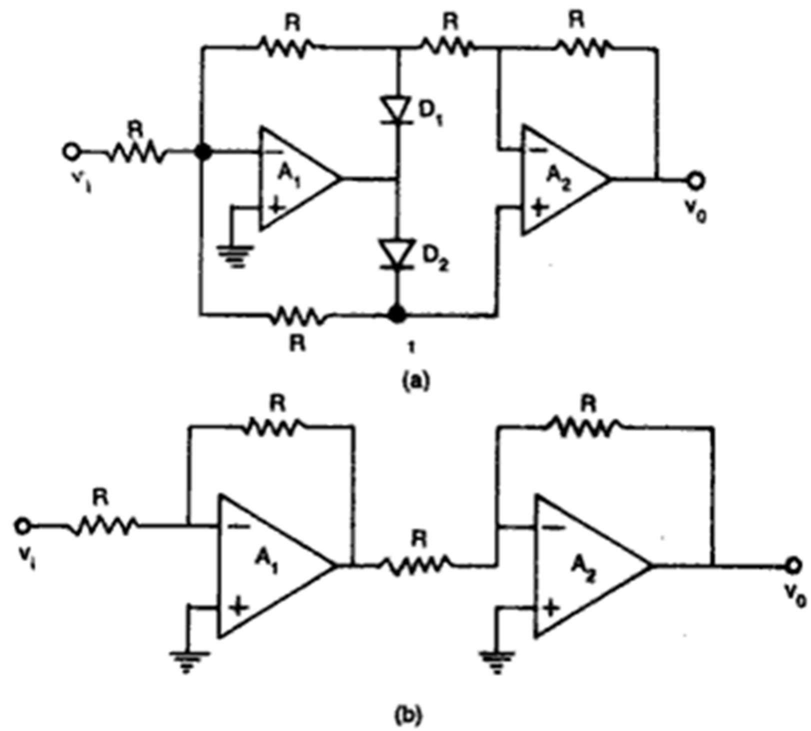
Half-wave rectifier



(a) Half-wave rectifier (b) waveforms

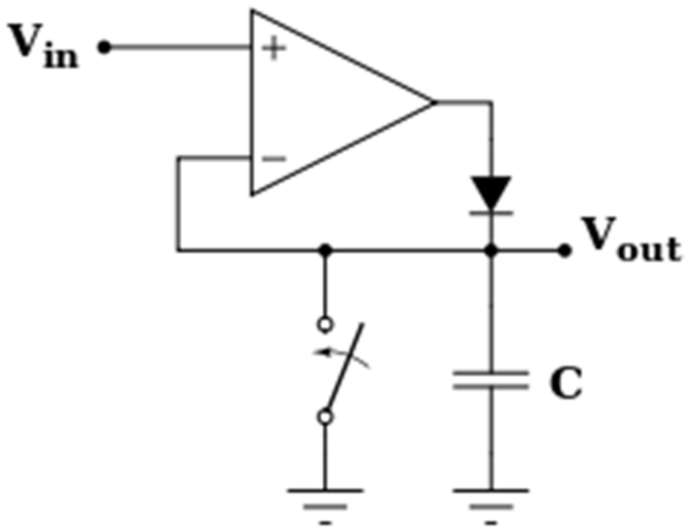
Full-wave rectifier

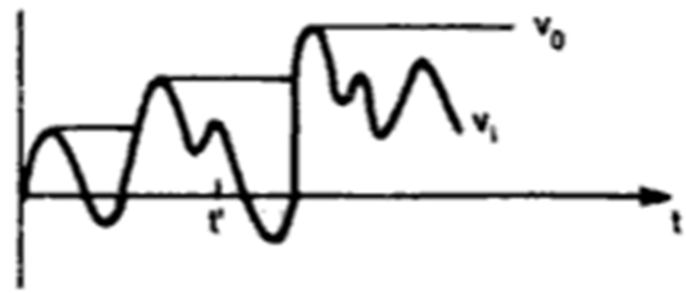
- When $v_i > 0$, (positive half cycle),
  - D_1-ON, D_2-OFF
  - $v_o = v_i$
- When $v_i < 0$, (negative half cycle),
  - D_1-OFF, D_2-ON
  - $v_o = v_i$



(a) Full-wave rectifier and (b) its equivalent circuit when $V_i > 0$

Peak detector

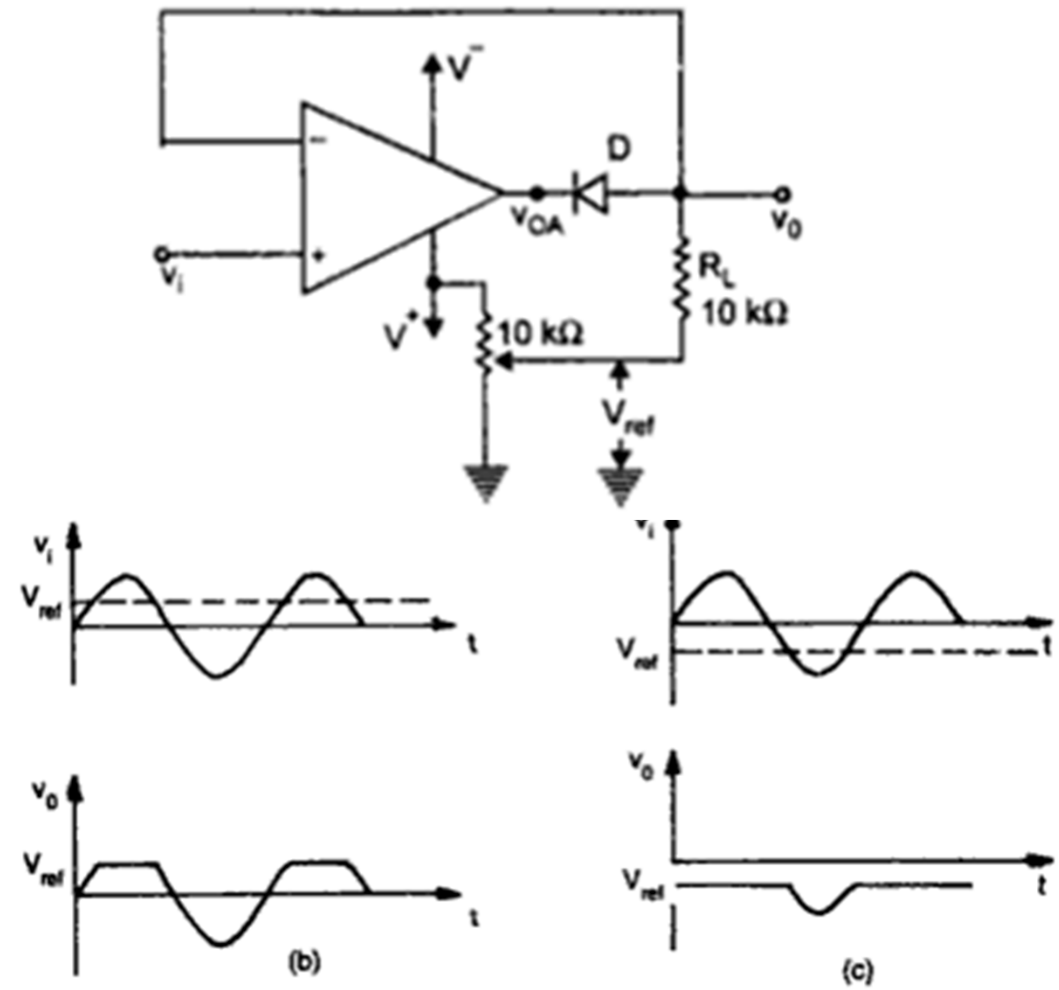




Clipper

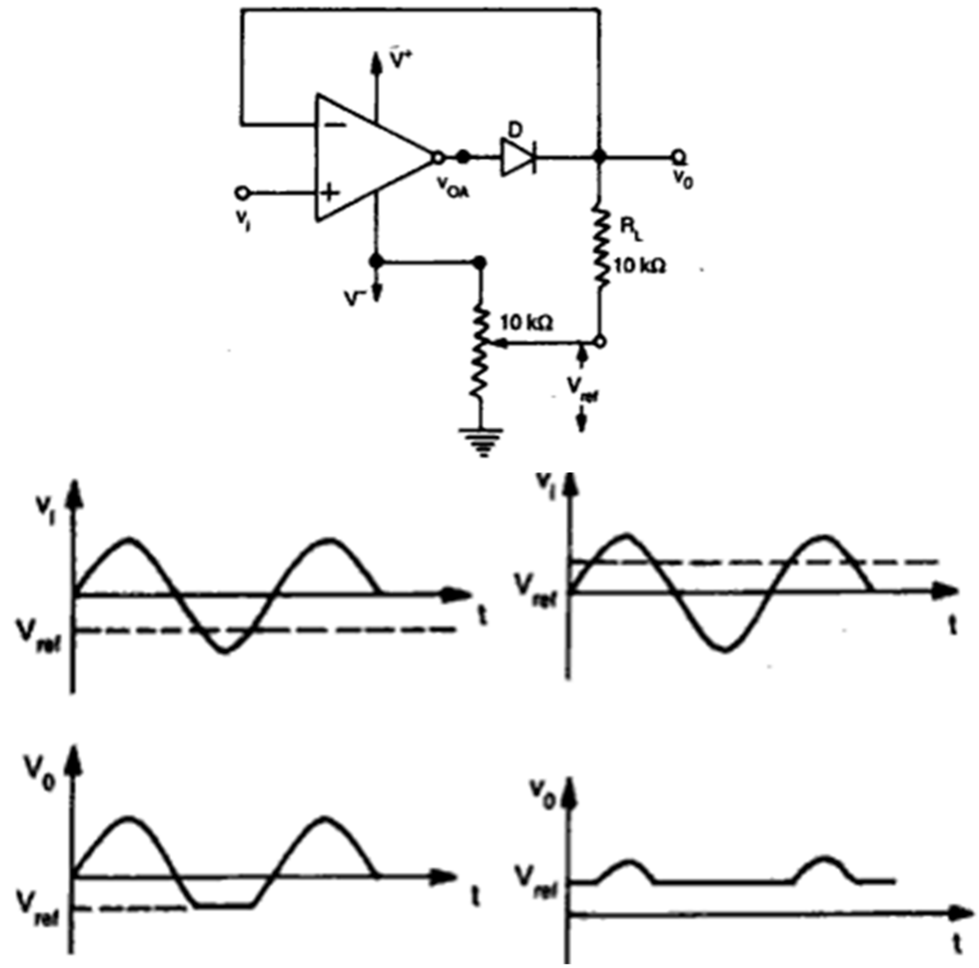
- Positive clipper
  - Positive reference
  - Negative reference
- Negative clipper
  - Positive reference
  - Negative reference

Positive clipper



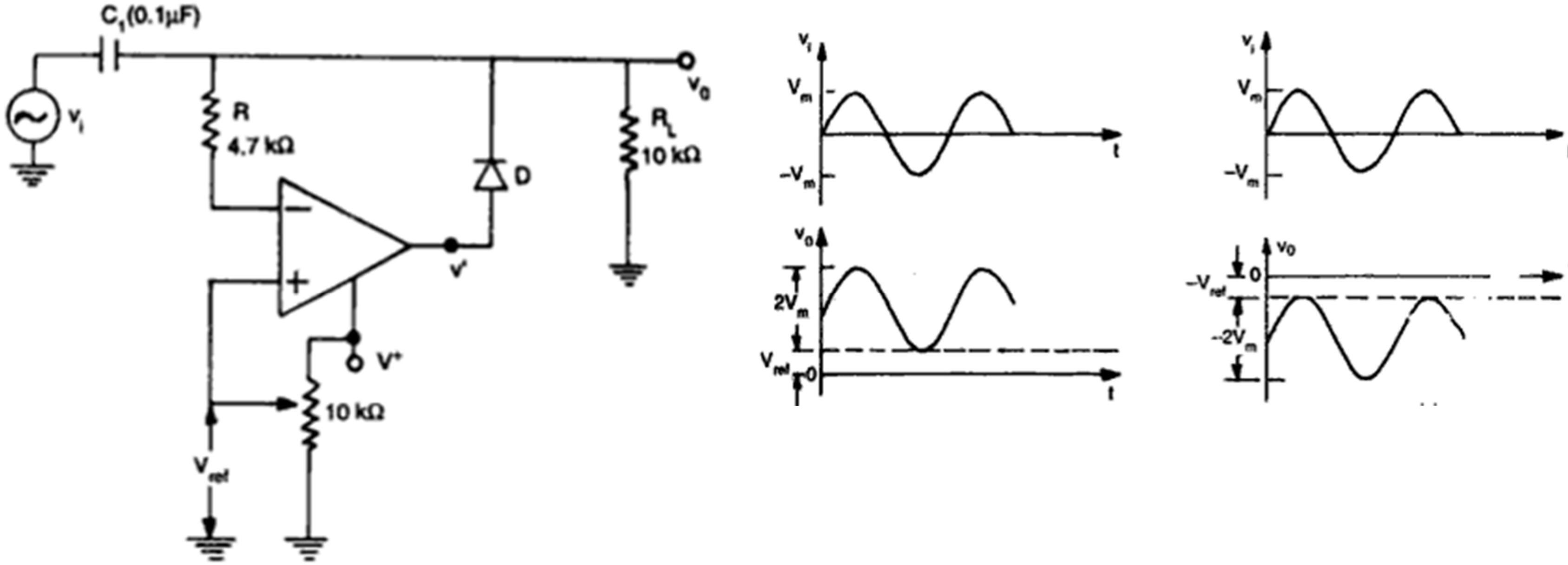
Positive reference **Negative reference**

Negative clipper



Negative reference **Positive reference**

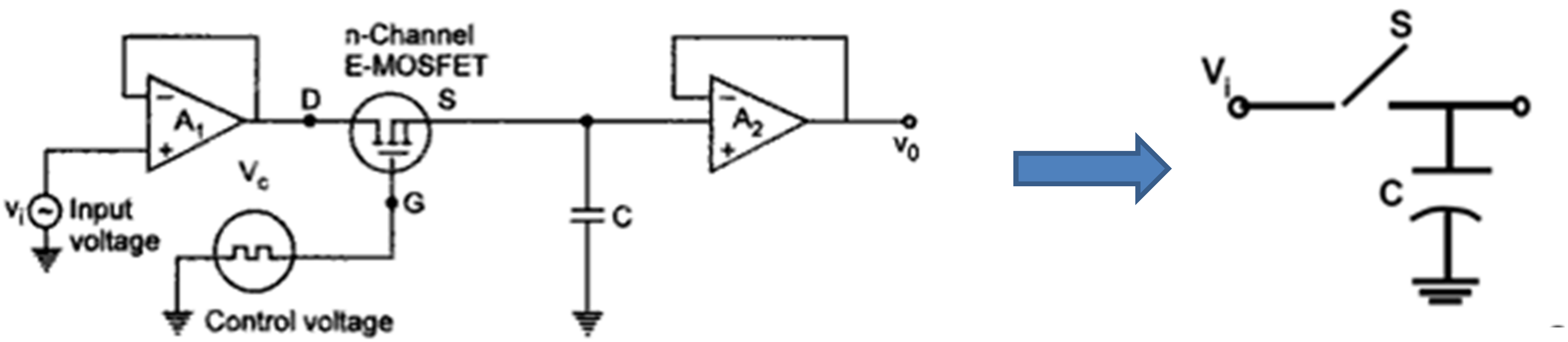
Clamper



C_1(0.1μF)
v_i
R
4.7 kΩ
D
R_L
10 kΩ
v_o
V'
V^+
10 kΩ
V_{ref}
V_m
$-V_m$
t
2V_m
V_{ref}
0
$-V_{ref}$
-2V_m

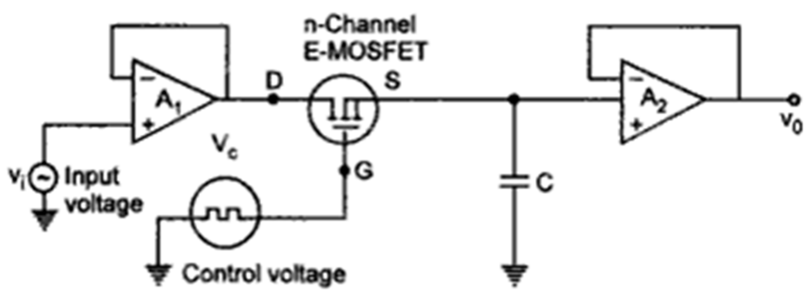
Sample and hold circuit

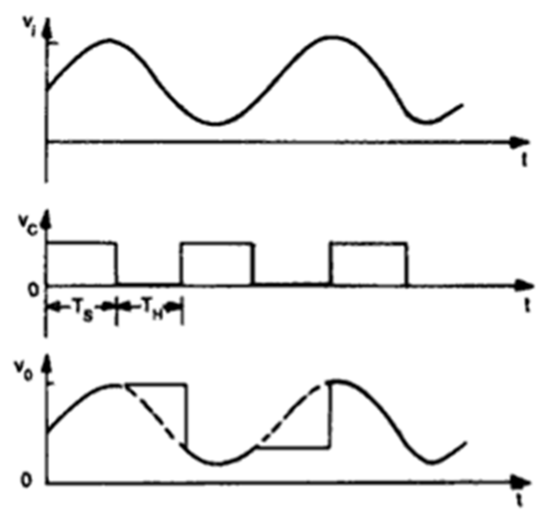
- **Signal** to be sampled is applied to drain of the MOSFET
- **Control voltage** given to the gate of the MOSFET



Sample and hold circuit

- V_c +Ve, MOSFET – ON, Capacitor charges to v_i (ON time)$\rightarrow V_o$
- V_c = 0 V, MOSFET is OFF, Capacitor cannot discharge through A_2 (High impedance of A_2), Capacitor holds the value $\rightarrow V_o$





Log amplifier

$$I_E = I_S\left(e^{\frac{qV_E}{kT}} - 1\right)$$

Base is grounded,

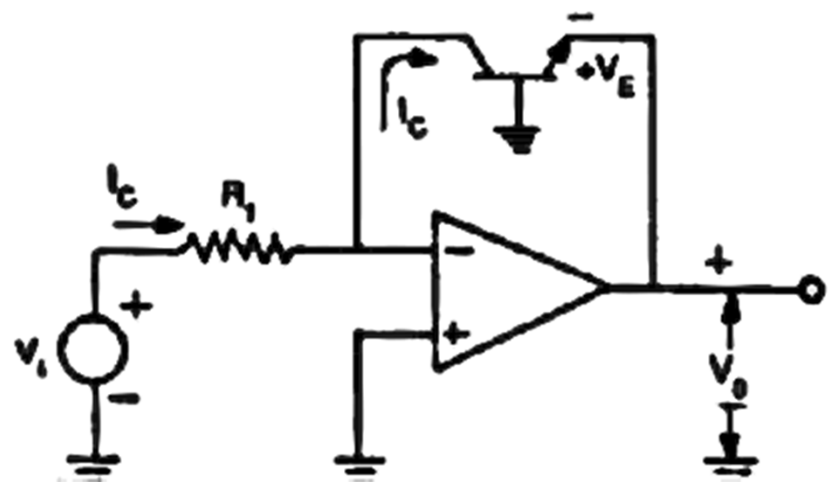
$$\therefore I_C = I_E = I_S\left(e^{\frac{qV_E}{kT}} - 1\right)$$

$$e^{\frac{qV_E}{kT}} = \frac{I_C}{I_S} + 1$$

$$e^{\frac{qV_E}{kT}} \approx \frac{I_C}{I_S}$$

Take natural log on both sides

$$V_E = \frac{kT}{q}\ln\left(\frac{I_C}{I_S}\right)$$



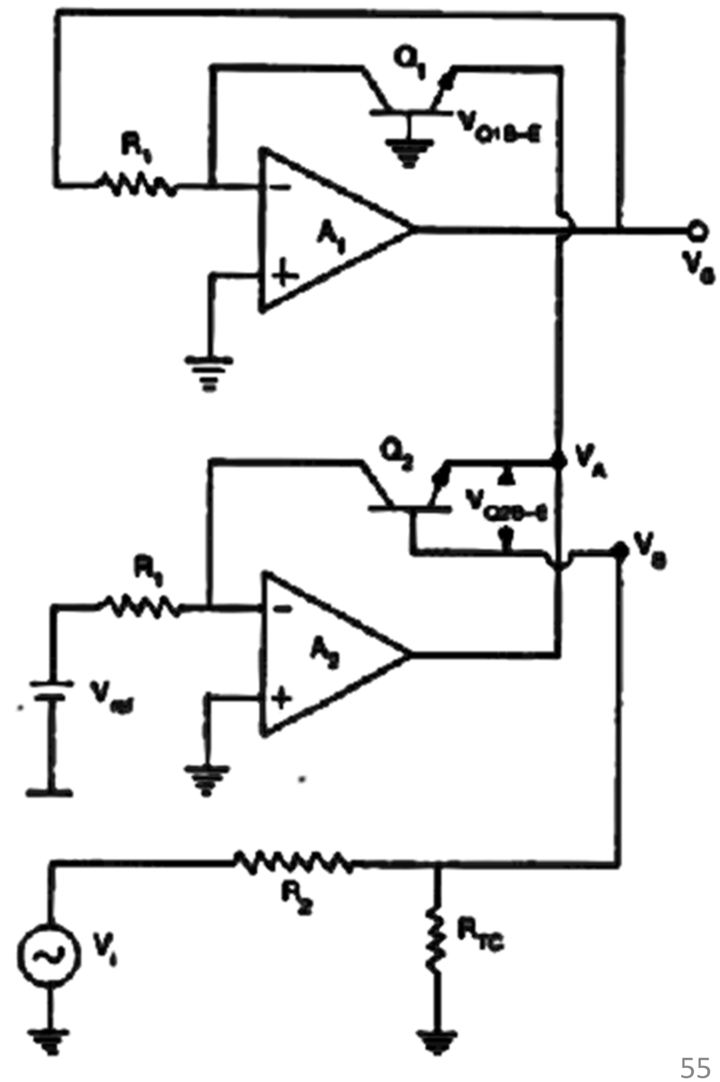
Also,

$$V_E = -V_o$$

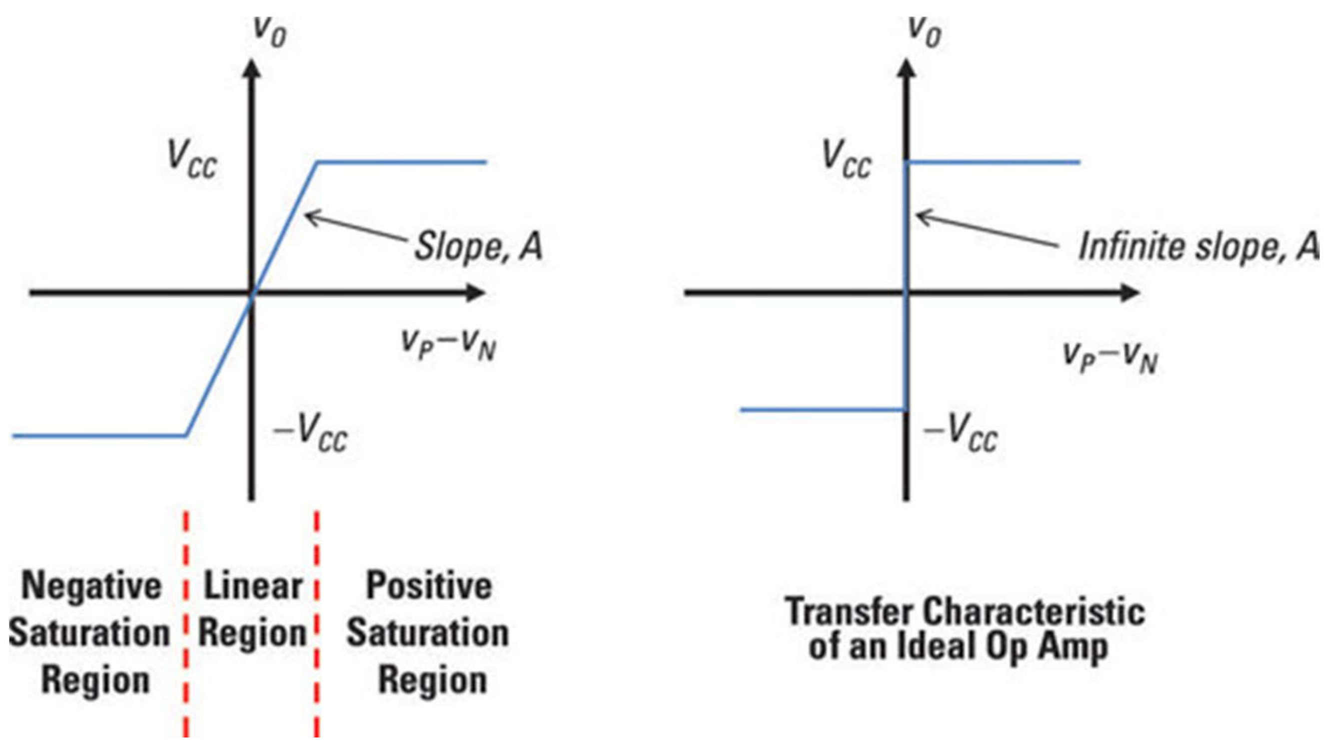
$$I_C = \frac{V_i}{R_1}$$

$$\therefore V_o = -\frac{kT}{q}\ln\left(\frac{V_i}{I_S R_1}\right)$$

Antilog amplifier



Transfer characteristics of op-amp



Negative saturated region: $v_O = -V_{CC}$ $\quad A_v(v_p - v_N) < -V_{CC}$

Linear active region: $v_O = A_v(v_p - v_N)$ $\quad -V_{CC} < A_v(v_p - v_N) < +V_{CC}$

Positive saturated region: $v_O = +V_{CC}$ $\quad A_v(v_p - v_N) > +V_{CC}$

Comparators and waveform generators

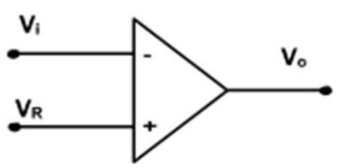
- Op-amp in open loop
  - Operates in non-linear fashion
- Open loop applications of op-amp
  - Comparators
  - Detectors
  - Converters etc.

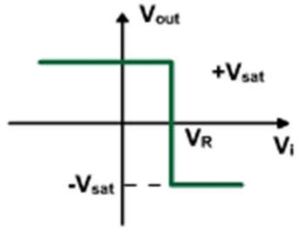
Comparator

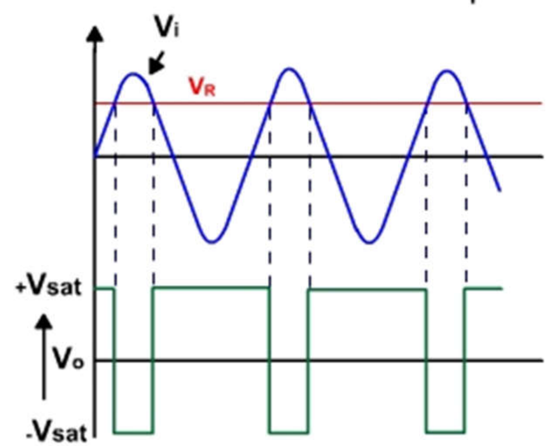
- An analog comparator has
  - **Two inputs**
    - A constant reference voltage V_R and other is a
    - Time varying signal v_i
  - **One output** v_O

$$v_o = -V_{sat} \qquad if\ v_i > V_R$$

$$v_o = +V_{sat} \qquad if\ v_i > V_R$$







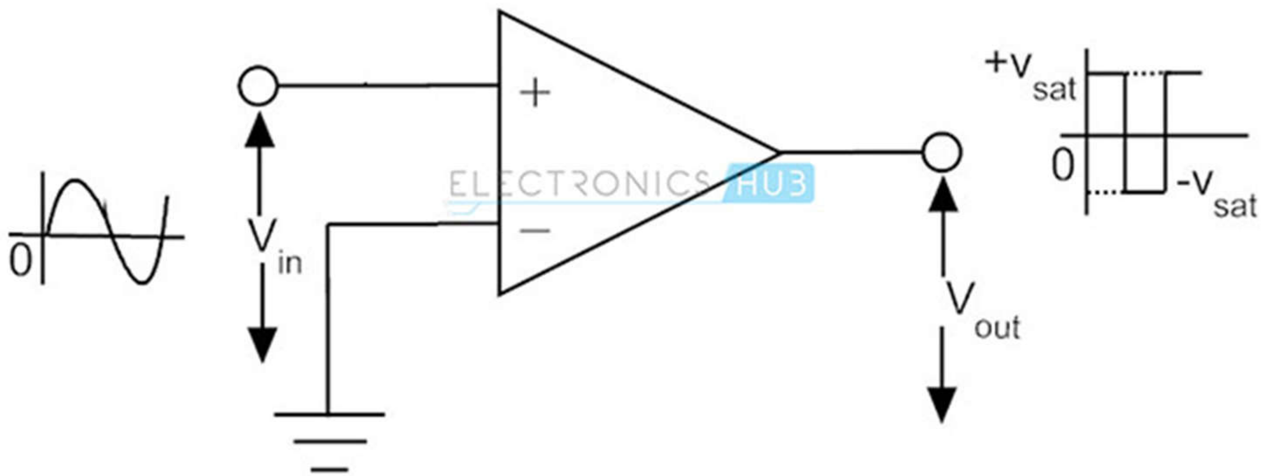
NO feedback
Inverting comparator

Non-inverting comparator

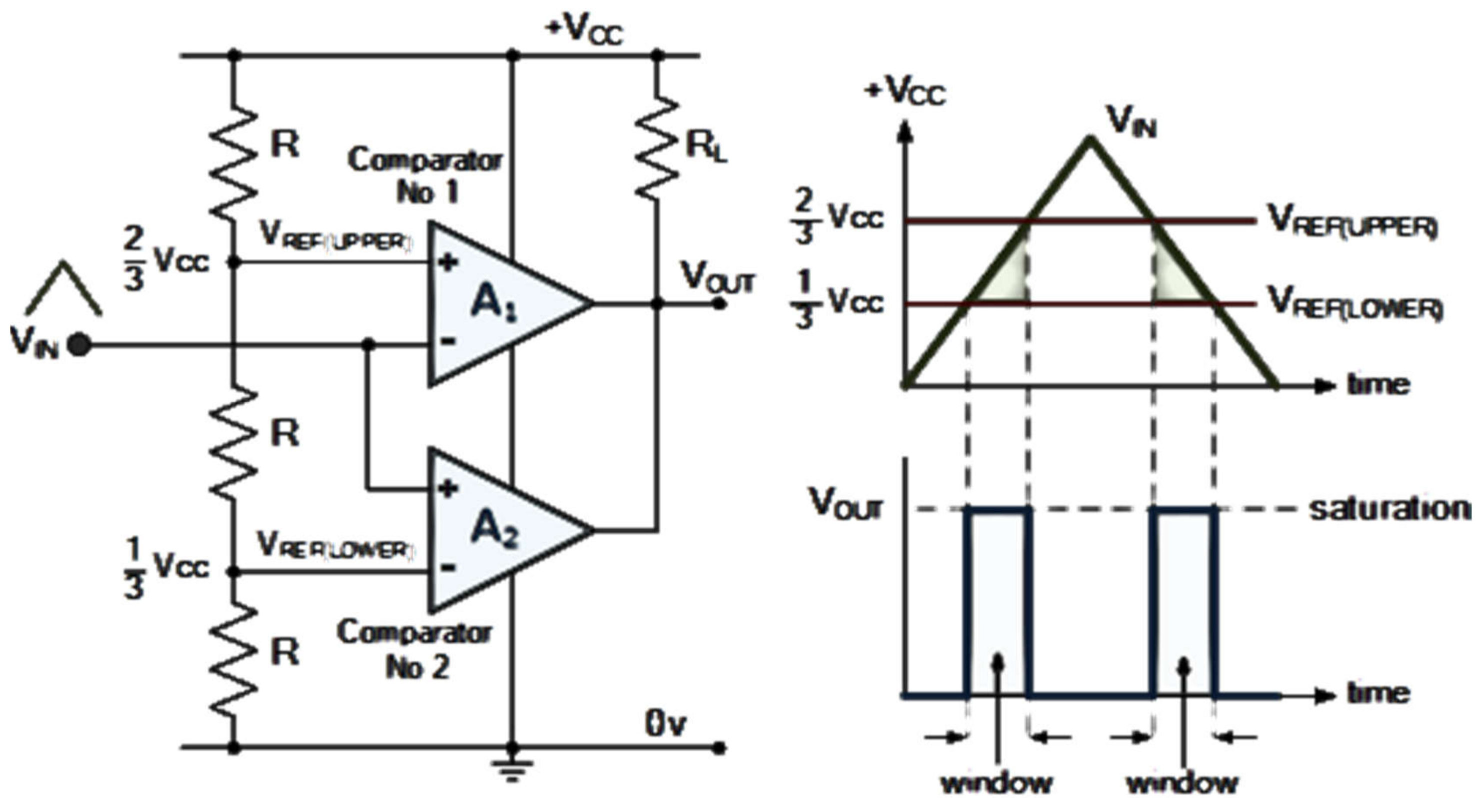
Applications of comparator

- Zero crossing detector
- Window detector

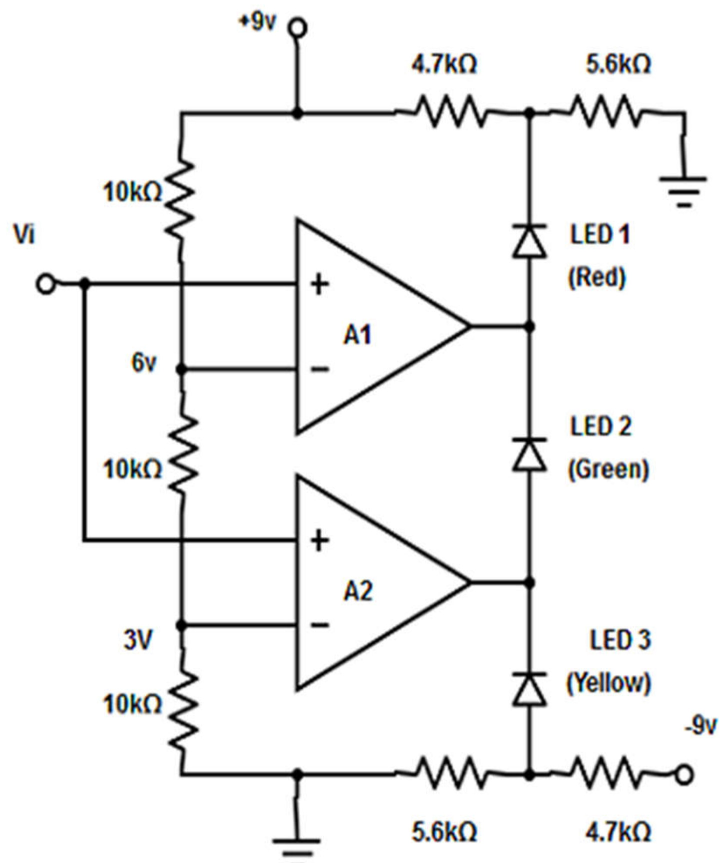
Zero crossing dectector



Window detector



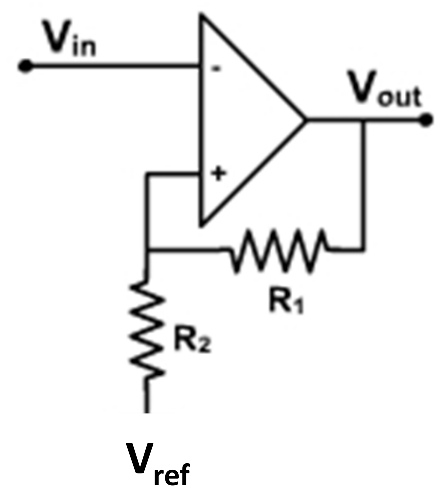
Three level comparator with LED



Input (V)	LED 3	LED 2	LED 1
< 3			
3 < vi < 6			
> 6			

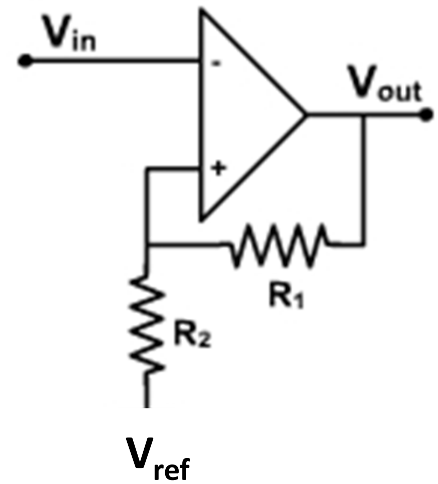
Regenerative comparator (Schmitt trigger)

- Input is given to inverting terminal
- Feedback voltage is given to non-inverting terminal
- Input triggers output every time it exceeds certain voltage levels
- The voltage levels are
  - Upper threshold voltage (V_{UT})
  - Lower threshold voltage (V_{LT})



Regenerative comparator (Schmitt trigger)

- Let, $v_{out} = +V_{sat}$



Then, voltage at non-inverting terminal is

$$V_{UT} = \frac{R_1}{R_1 + R_2} V_{ref} + \frac{R_2}{R_1 + R_2} V_{sat}$$

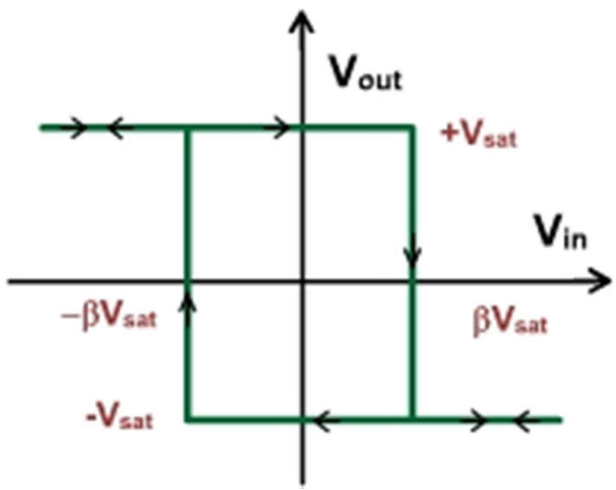
As long as $V_{in} < V_{UT}$, $V_{out} = V_{sat}$

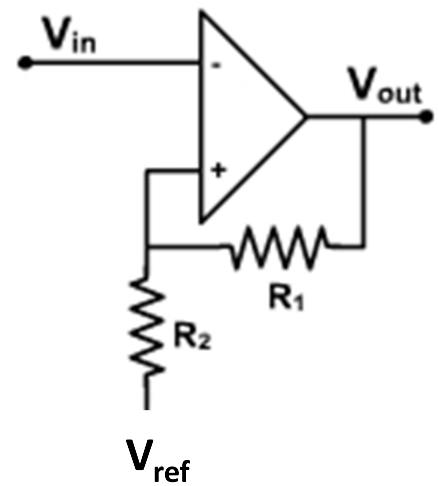
If V_{in} is just greater than V_{UT}, $v_{out} = -V_{sat}$

Then, voltage at non-inverting terminal is

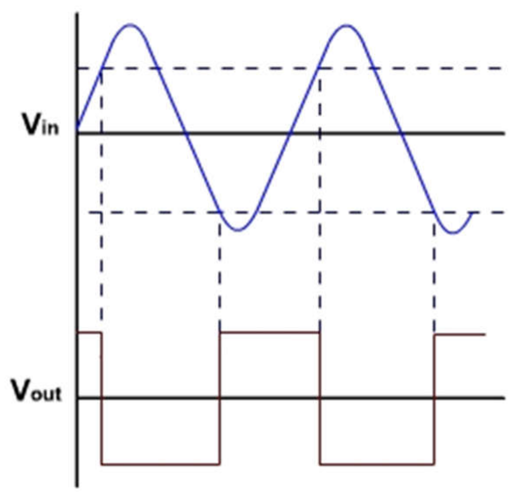
$$V_{LT} = \frac{R_1}{R_1 + R_2} V_{ref} - \frac{R_2}{R_1 + R_2} V_{sat}$$

Regenerative comparator (Schmitt trigger)



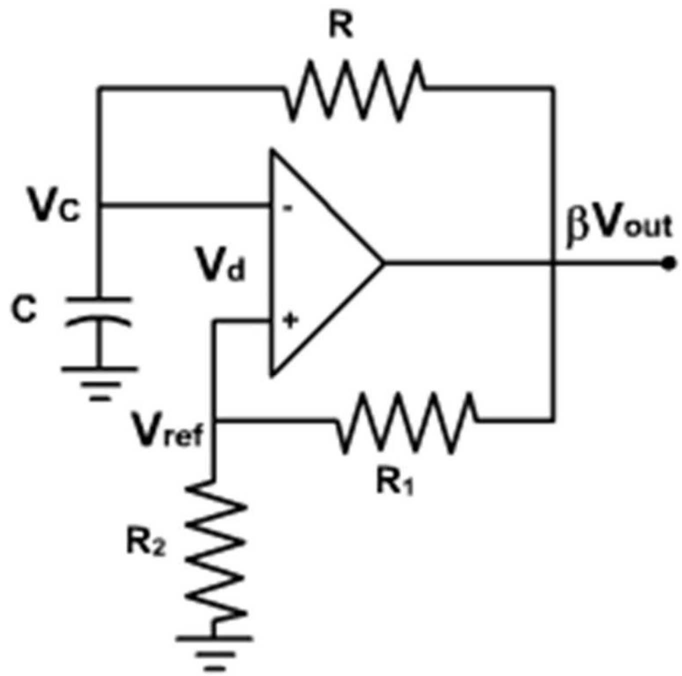


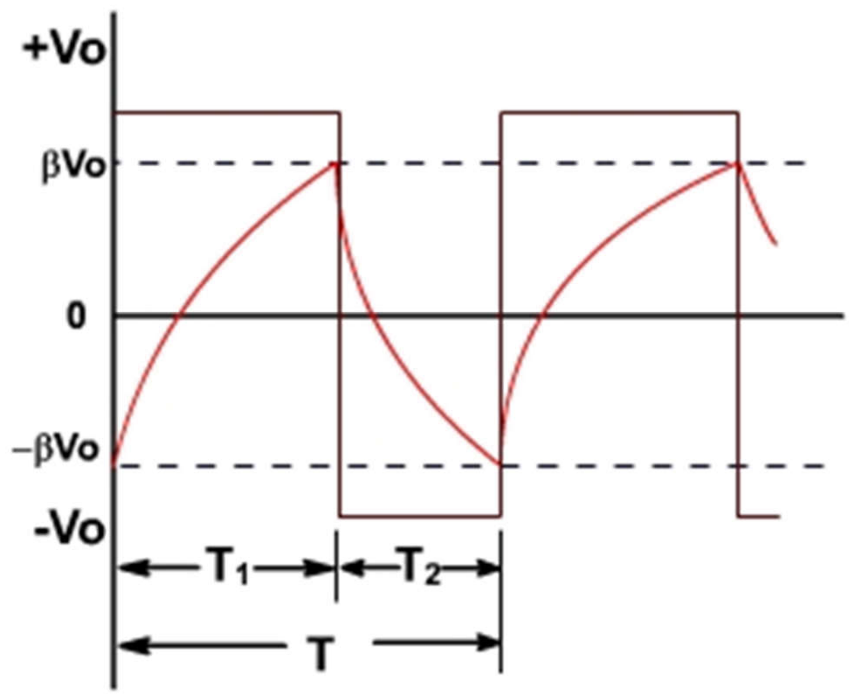
The transfer characteristic of Schmitt trigger circuit



If sinusoidal input is given, square wave results

Square wave generator (Astable multivibrator)





$$\beta = \frac{R_2}{R_1 + R_2}$$

Square wave generator (Astable multivibrator)

- Let, $v_o = +V_{sat}$

Voltage across the capacitor

$$v_c(t) = V_f + (V_i - V_f)e^{-t/RC}$$

Final value, $V_f = +V_{Sat}$

Initial value, $V_i = -\beta V_{Sat}$

$$\therefore v_c(t) = V_{Sat} - V_{Sat}(1+\beta)e^{-t/RC}$$

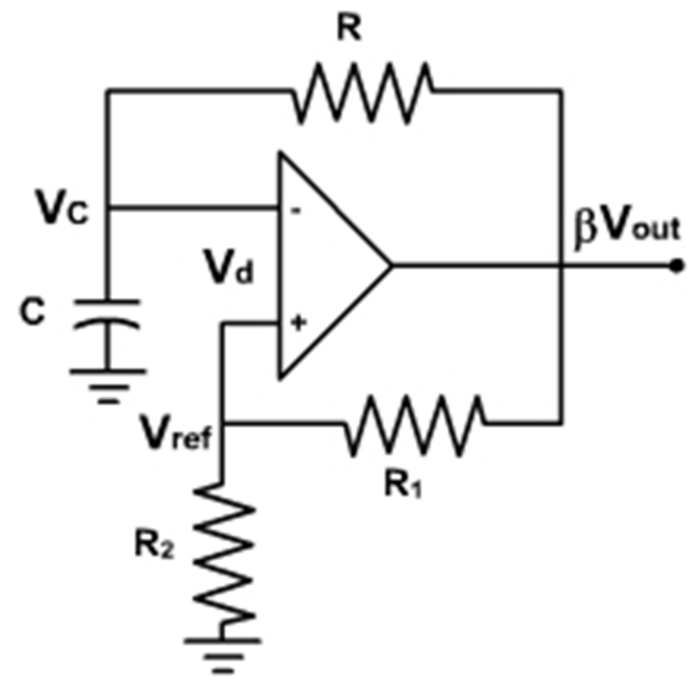
At $t = T_1$

$$v_c(T_1) = \beta V_{sat}$$

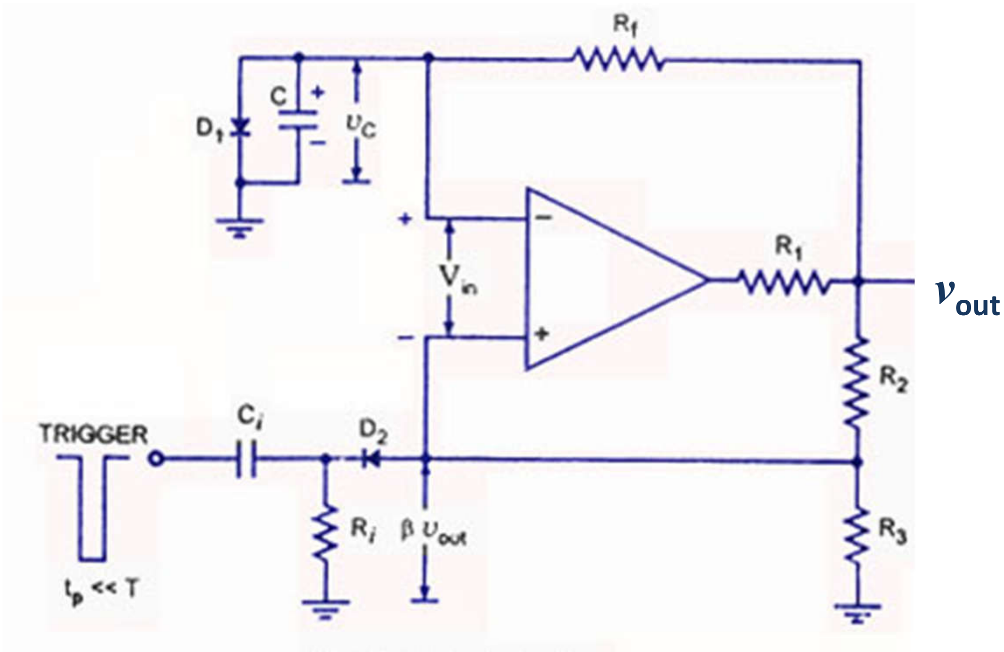
$$\beta V_{sat} = V_{Sat} - V_{Sat}(1+\beta)e^{-T_1/RC}$$

Solving

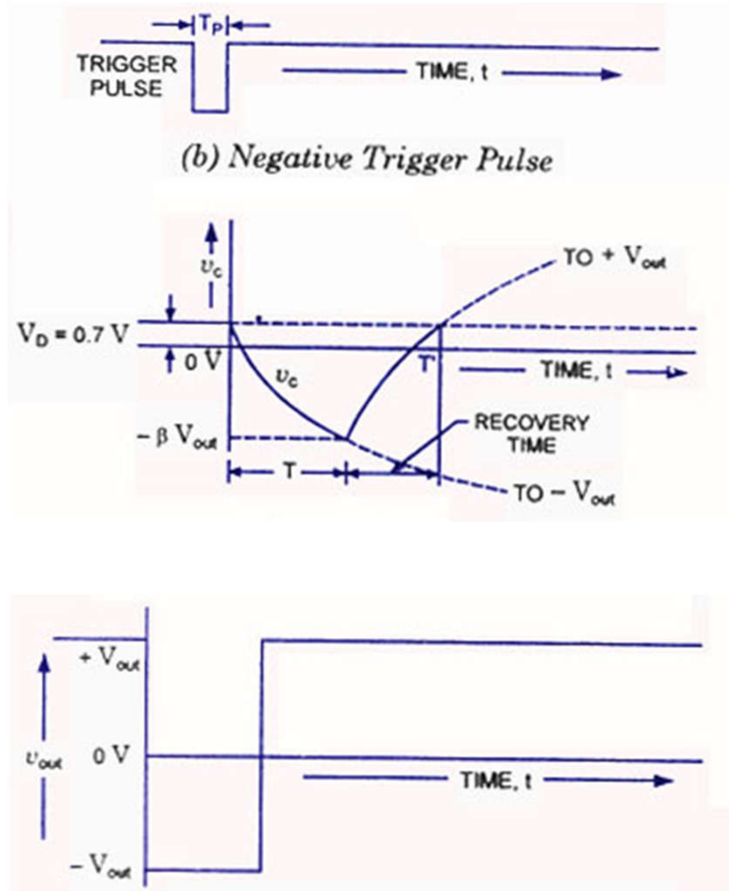
$$T = RC\ln\left(\frac{1+\beta}{1-\beta}\right)$$



Monostable multivibrator



- For generating single output pulse whose pulse duration can be varied.
- Requires triggering pulse



Output voltage waveform

Monostable multivibrator

- Find the gain of the circuit
- Ans: -8