APPLICATIONS OF OP- AMPS

LINEAR APPLICATIONS

- Adder
- Subtractor
- Voltage follower
- Current to voltage converter
- Voltage to current converter
- Integrator
- Differentiator
- Active filters

Non-linear applications

- Comparators
- Logarithmic amplifiers
- Exponential amplifiers
- Peak detectors
- Precision rectifiers
- Waveform generators
- Clippers & clampers

Non Linear Applications:

Precision rectifiers.

- The major limitation of ordinary diode is that it cannot rectify voltages below $\mathbf{v}_{\gamma}$ (~ 0.6 V), the cut-in voltage of the diode.

- A circuit that acts like an ideal diode can be designed by placing a diode in the feedback loop of an op-amp as in Fig. 4.10 (a). Here the cut-in voltage is divided by the open loop gain A_{0L} (~ 10^4) of the op- amp so that v_{γ} is virtually eliminated. When the input $V_i > V_{\gamma} / A_{OL}$ then v_{oA}, the output of the op-amp exceeds V_{γ} and the diode D conducts. Thus the circuit acts like a voltage follower for input $v_i > V_{\gamma} / A_{0L}$ (i.e., $0.6/10^4 = 60\mu v$) and the output v_0 follows the input voltage v_i during the positive half cycle as shown in Fig. 4.10 (b).

- When v_i is negative or less than V_γ/A_{0L}, the diode *D* is *off* and no current is delivered to the load R_L except for small bias current of the op-amp and the reverse saturation current of the diode. This circuit is called the precision diode and is capable of rectifying input signals of the order of mill volt. Some typical applications of a precision diode discussed are:
- Half-wave Rectifier
- Full-Wave Rectifier
- Peak-Value Detector.
- Clipper.
- Clamper.

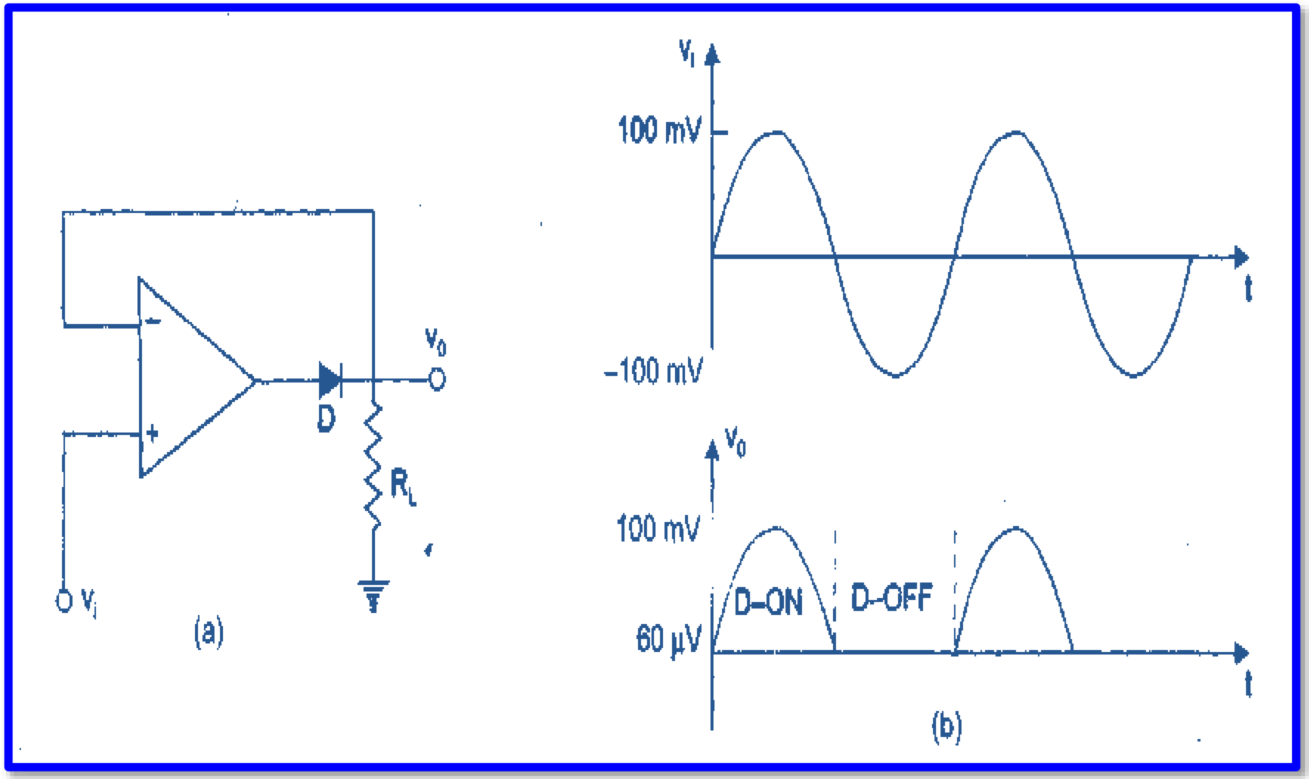
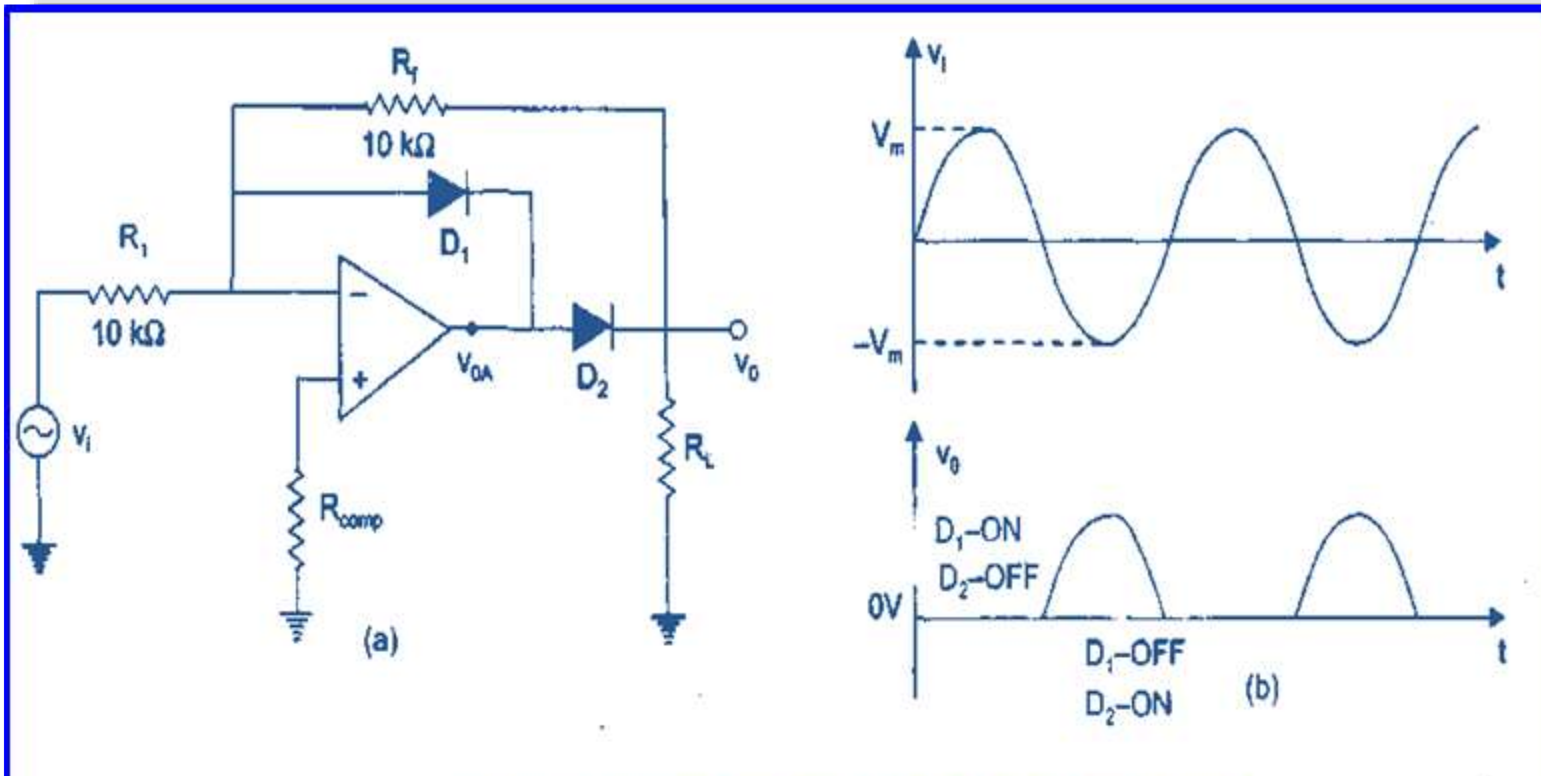


Fig. (a) Precision diode, (b) Input and output waveforms



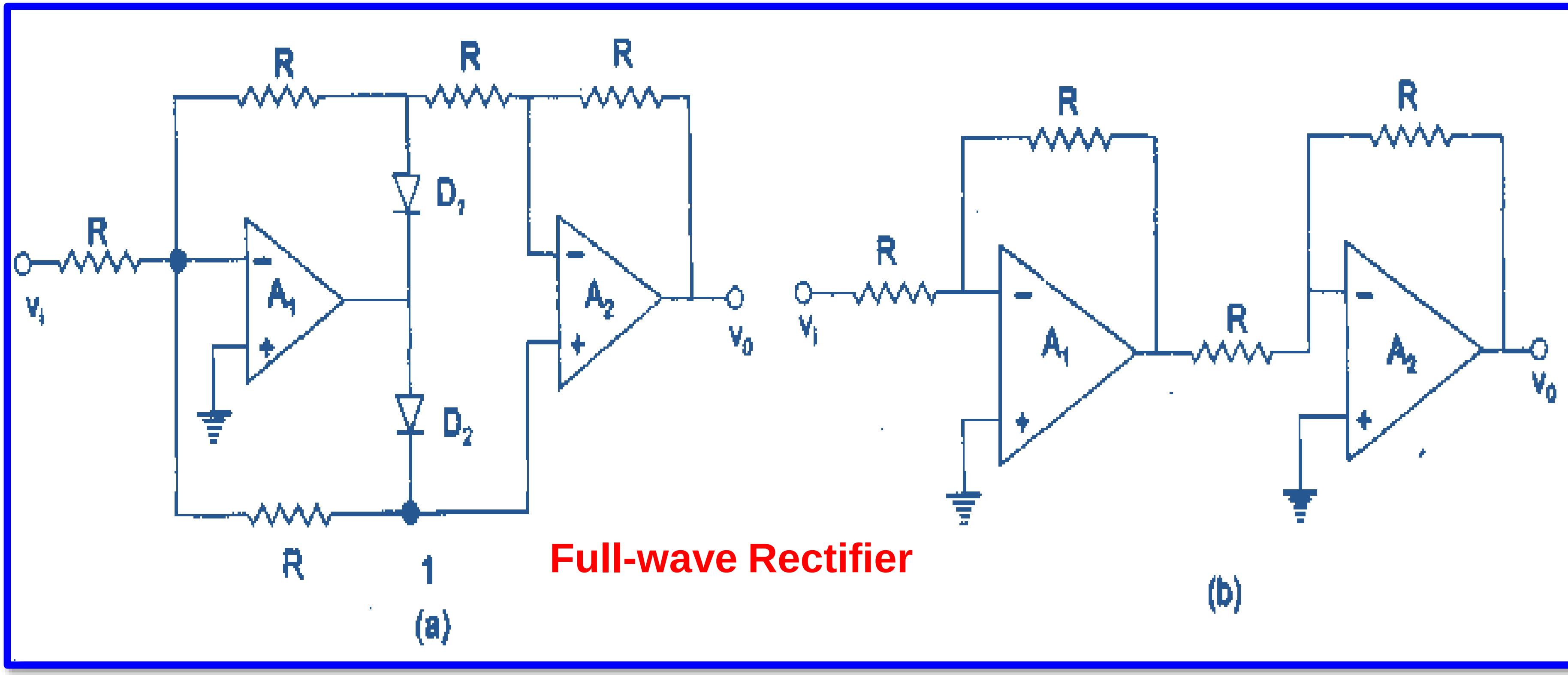
(a) Ideal half-wave rectifier, (b) Input/output waveforms

When V_i is +ve, V_{oa} is –ve. D_2 is reverse biased and output is zero. When V_i is -ve, R_f=R_1, V_{oa} is +ve, and D_2 conducts even when the input is < 0.7V. The op-amp should be a high speed version as it alternates between open loop & closed loop operations. High Slew rate is required as the input passes through zero, V_{oa} must change from 0.6V to -0.6V. If the diodes are reversed, -ve output occurs.

An inverting amplifier can be converted into an ideal half-wave rectifier by adding two diodes as shown in Fig. 4.11 (a). When v_i is positive, diode D_1 conducts causing v_{0A} to go to negative by one diode drop (~ 0.6 V). Hence diode D_2 is reverse biased. The output voltage v_0 is zero, because, for all practical purposes, no current flows through R_f and the input current flows through D_1.

For negative input, i.e., $v_i < 0$, diode D_2 conducts and D_1 is *off.* The negative input v_i forces the op-amp output v_{0A} positive and causes D_2 to conduct. The circuit then acts like an inverter for $R_f = R_1$ and output v_0 becomes positive.

The input, output waveforms are shown in Fig. 4.11 (b). The op-amp in the circuit of Fig. 4.11 (a) must be a high speed op-amp since it alternates between open loop and closed loop operations. The principal limitation of this circuit is the slew rate of the op-amp. As the input passes through zero, the op-amp output v_{oA} must change from 0.6 V to - 0.6 V or vice-versa as quickly as possible in order to switch over the conduction from one diode to the other. The circuit of Fig. 4.11(a) provides a positive output. However, if both the diodes are reversed, then only positive input signal is transmitted and gets inverted. The circuit, then provides a negative output.



(a) Precision full wave rectifier, (b) Equivalent circuit for $v_i > 0$; D_1 is on and D_2 is OFF; op-amp A_1 and A_2 operate as inverting amplifier

A full wave rectifier or absolute value circuit is shown in Fig. 4.12 (a). For positive input, i.e. $v_i > 0$, diode D_1 is *on* and D_2 is *off.* Both the op-amps A_1 and A_2 act as inverter as shown in equivalent circuit in Fig. 4.12 (b). It can be seen that $v_0 = v_i$

For negative input, i.e. $v_i < 0$, diode D_1 is *off* and D_2 is *on.* The equivalent circuit is shown in Fig. 4.12 (c). Let the output voltage of op-amp A_1 be v. Since the differential input to A_2 is zero, the inverting input terminal is also at voltage v. KCL at node 'a' gives

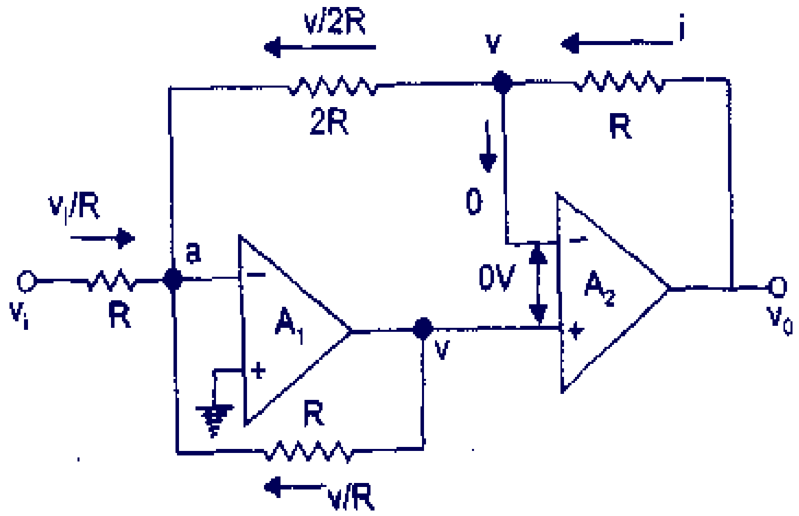
$$\frac{v_i}{R} + \frac{v}{2R} + \frac{v}{R} = 0$$

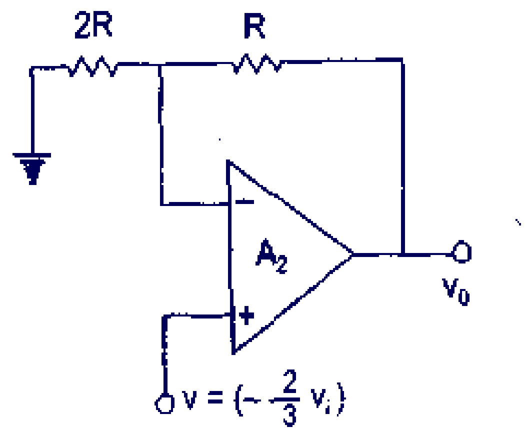
$$v = -\frac{2}{3} v_i \longrightarrow$$

The equivalent circuit of Fig. 4.12 (c) is a non-inverting amplifier as shown in Fig. 4.12 (d). The output v_0 is,

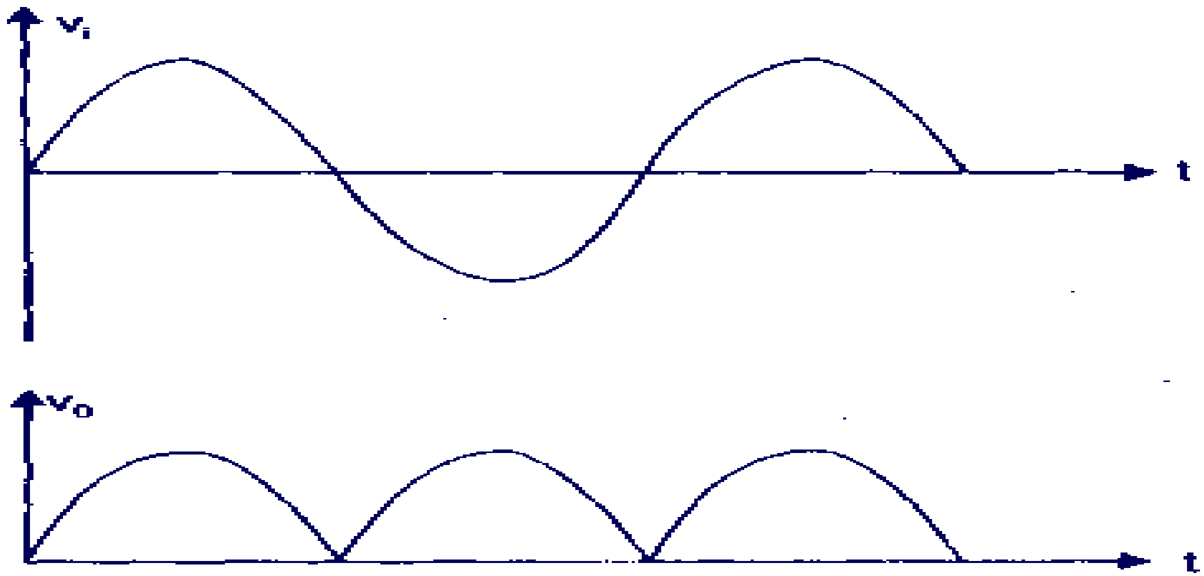
$$v_o = \left(1 + \frac{R}{2R}\right)\left(-\frac{2}{3} v_i\right) = v_i \longrightarrow$$

Hence for $v_i < 0$, the output is positive. The input and output waveforms are shown in Fig. 4.12 (e). The circuit is also called an absolute value circuit as output is positive even when input is negative. For example, the absolute value of | +2 | and | -2 | is +2 only. It is possible to obtain negative outputs for either polarity of input simply by reversing the diodes.





Equivalent circuit for v, < 0, (d) Equivalent circuit of (c)



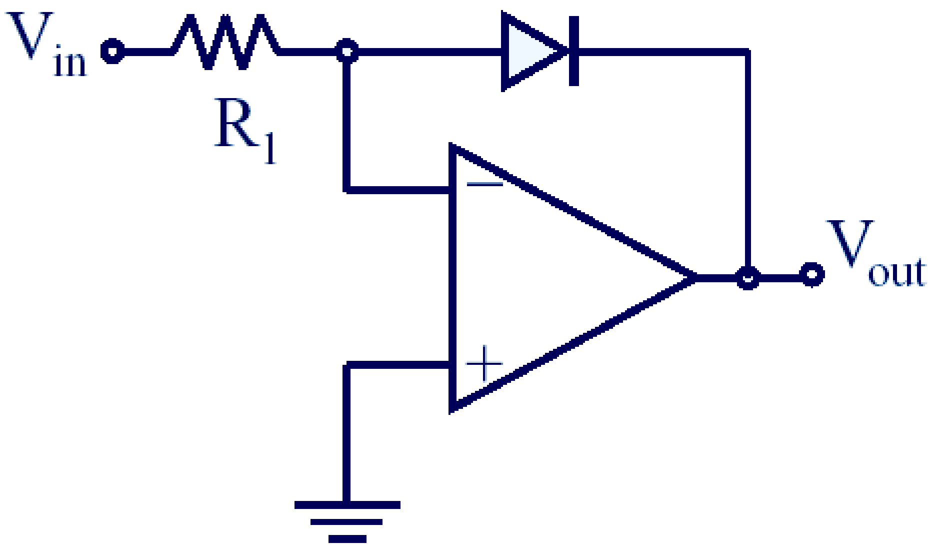
(e) Input and output waveforms

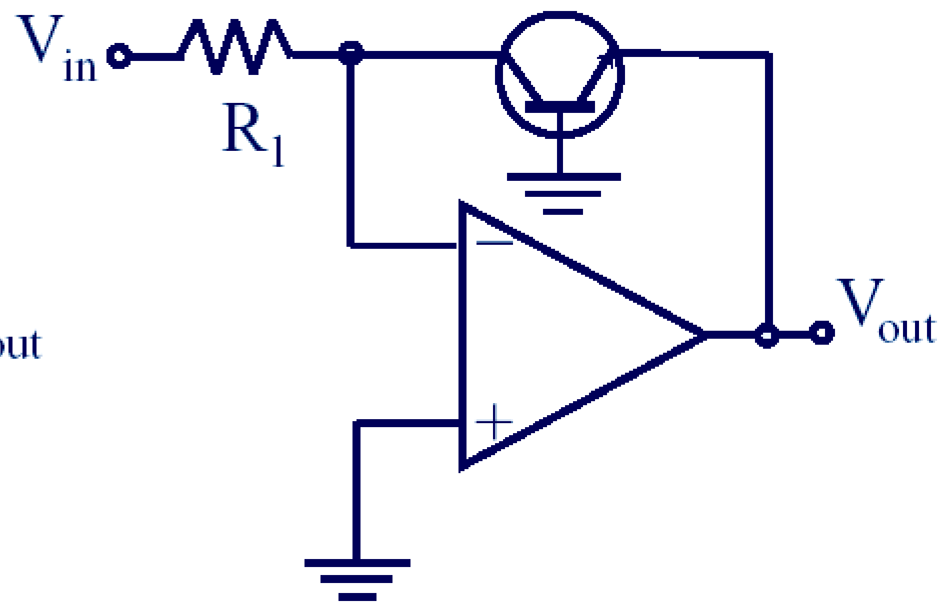
LOG -AMPLIFIER

Log Amplifiers

The basic log amplifier produces an output voltage as a function of the logarithm of the input voltage; i.e.,
$V_{out} = -K \ln(V_{in})$, where K is a constant.
Recall that the a diode has an exponential characteristic up to a forward voltage of approximately 0.7 V. Hence, the semiconductor pn junction in the form of a diode or the base emitter junction of a BJT can be used to provide a logarithm characteristic.

Diode & BJT Log Amplifiers





$$V_{out} \cong -0.025 \ln\left(\frac{V_{in}}{I_R R_1}\right) \text{ V}$$

$$V_{out} \cong -0.025 \ln\left(\frac{V_{in}}{I_{EBO} R_1}\right) \text{ V}$$

I_R = reverse leakage current

I_{EBO} = emitter-to-base leakage current

There are several applications of log and antilog amplifiers.

- Antilog computation may require functions such as ln *x*, log *x* or sinh *x*. These can be performed continuously with log-amps.
- One would like to have direct dB display on digital voltmeter and spectrum analyzer. Log-amp can easily perform this function.
- Log-amp can also be used to compress the dynamic range of a signal.

Log Amplifier

The fundamental log-amp circuit is shown in Fig. 4.34 (a) where a grounded base transistor is placed in the feedback path. Since the collector is held at virtual ground and the base is also grounded, the transistor's voltage-current relationship becomes that of a diode and is given by,

$$V_{0\ \text{comp}} = \left(1 + \frac{R_2}{R_{TC}}\right)\frac{kT}{q}\ln\left(\frac{V_i}{V_{ref}}\right)$$

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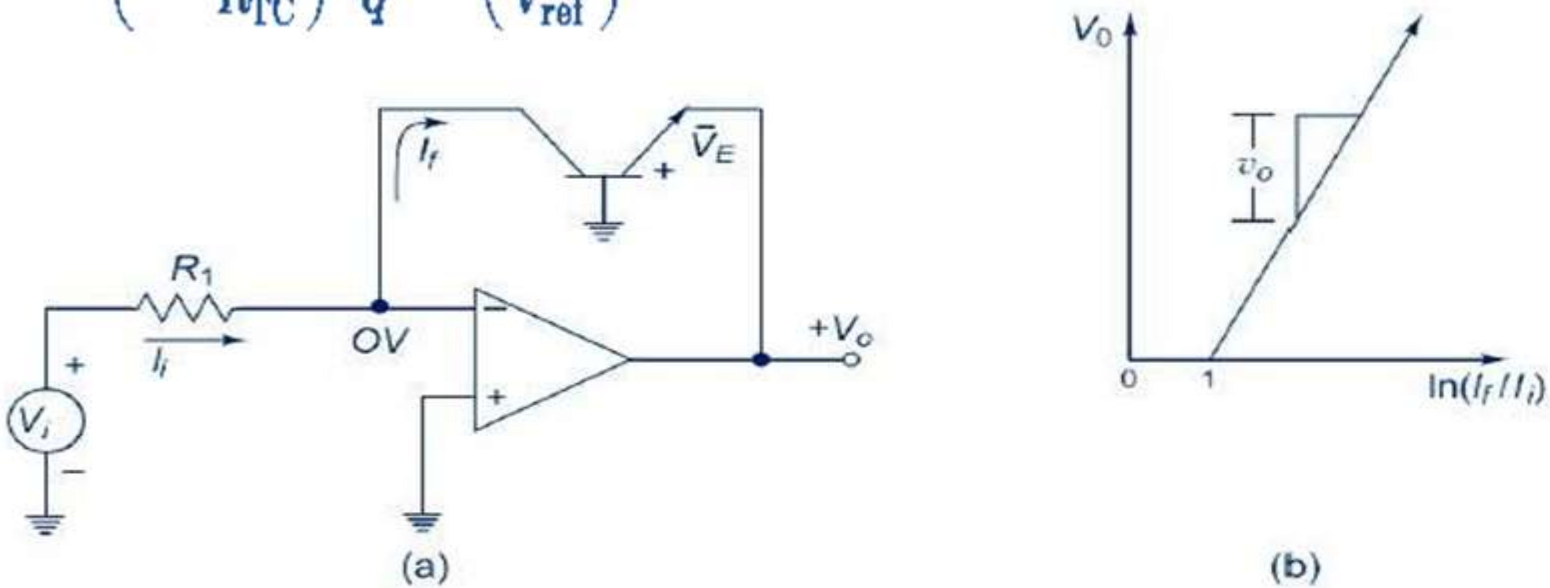


Logarithmic Amplifier (a) Fundamental circuit and (b) Its logarithmic characteristics

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

Since, $I_C = I_E$ for a grounded base transistor

Since $I_E = I_C$

$$I_C = I_s\left(e^{qV_E/kT} - 1\right)$$

I_S = emitter saturation current = 10^{-13} A
k = Boltzmann's Constant
T = absolute temperature (in ^{0}K)

Therefore, $\frac{I_C}{I} = \left(e^{qV_E/kT} - 1\right)$

or, $e^{qV_E/kT} = \frac{I_C}{I_s} + 1 \approx \frac{I_C}{I_s}$

Taking natural Log on both sides, we get

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

From Fig.

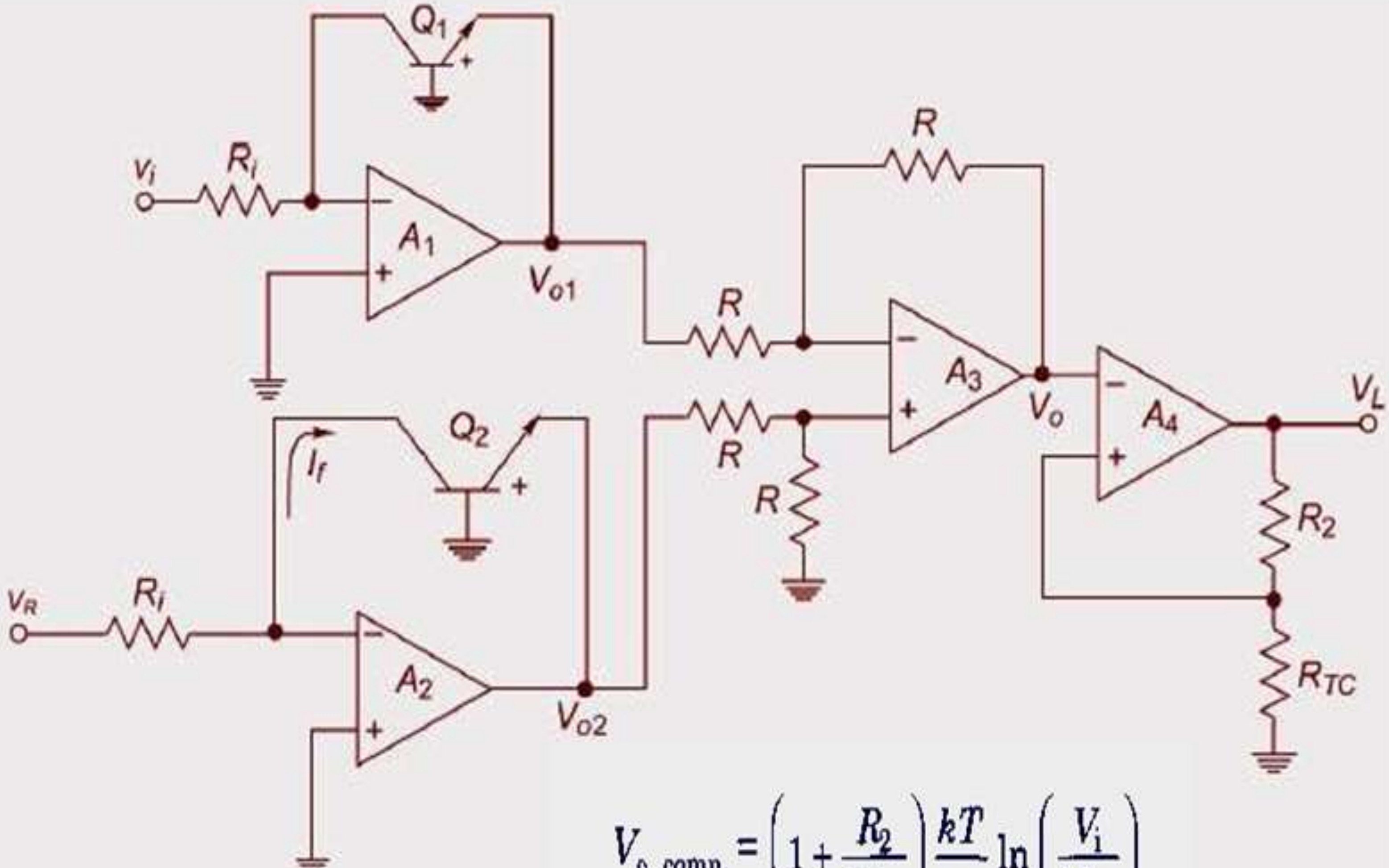
$$I_C = \frac{V_i}{R_1}$$

$$V_E = -V_o$$

$$V_o = -\frac{kT}{q}\ln\left(\frac{V_i}{R_1 I_s}\right) = -\frac{kT}{q}\ln\left(\frac{V_i}{V_{ref}}\right)$$

The circuit, however, has one problem.

- **The emitter saturation current I_S varies from transistor to transistor and with temperature. Thus a stable reference voltage V_{ref} cannot be obtained.**
- **This is eliminated by the circuit given in Fig. 4.18 (b). The input is applied to one log-amp, while a reference voltage is applied to another log-amp. The two transistors are integrated close together in the same silicon wafer. This provides a close match of saturation currents and ensures good thermal tracking.**



$$V_{o\ comp} = \left(1 + \frac{R_2}{R_{TC}}\right)\frac{kT}{q}\ln\left(\frac{V_i}{V_{ref}}\right)$$

Logarithmic amplifier with compensation of emitter saturation current

Assume, $Is_1 = Is_2 = I_s$ →
and then, V_1
=

$$V_1 = -\frac{kT}{q} ln\left(\frac{V_i}{R_1 I_s}\right) \qquad 4.40$$

$$V_2 = -\frac{kT}{q} ln\left(\frac{V_{ref}}{R_1 I_s}\right) \longrightarrow$$

$$V_o = V_2 - V_1 = -\frac{kT}{q}\left[ln\left(\frac{V_i}{R_1 I_s}\right) - ln\left(\frac{V_{ref}}{R_1 I_s}\right)\right] \longrightarrow$$

$$V_o = \frac{kT}{q} ln\left(\frac{V_i}{V_{ref}}\right) \longrightarrow$$

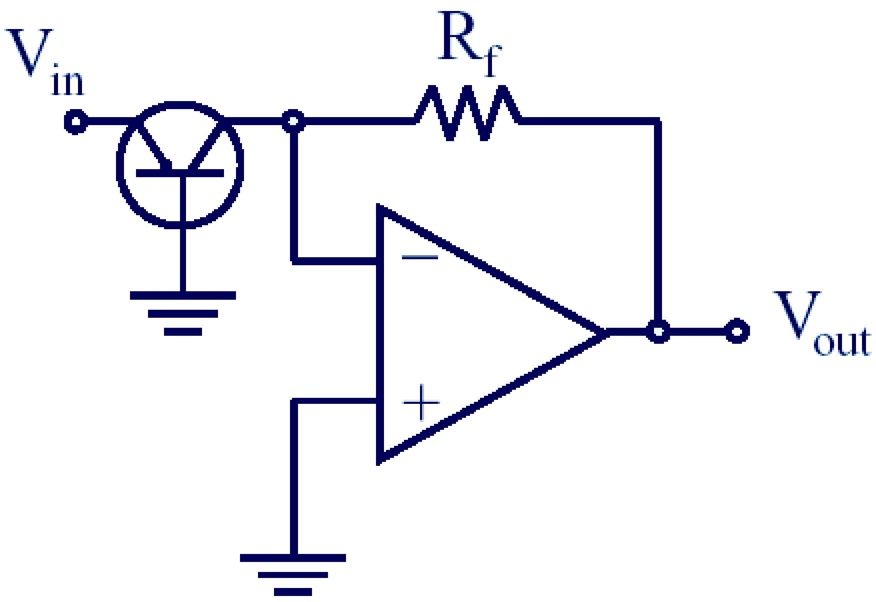
Thus reference level is now set with a single external voltage source. Its dependence on device and temperature has been removed. The voltage V_o is still dependent upon temperature and is directly proportional to T. This is compensated by the last op-amp stage A_4 which provides a non-inverting gain of $(1 + R_2/R_{TC})$. NOW, the output voltage is,

$$V_{o\ comp} = \left(1 + \frac{R_2}{R_{TC}}\right)\frac{kT}{q}\ln\left(\frac{V_i}{V_{ref}}\right) \longrightarrow$$

Where R_{TC} IS A PTC THERMISTOR.

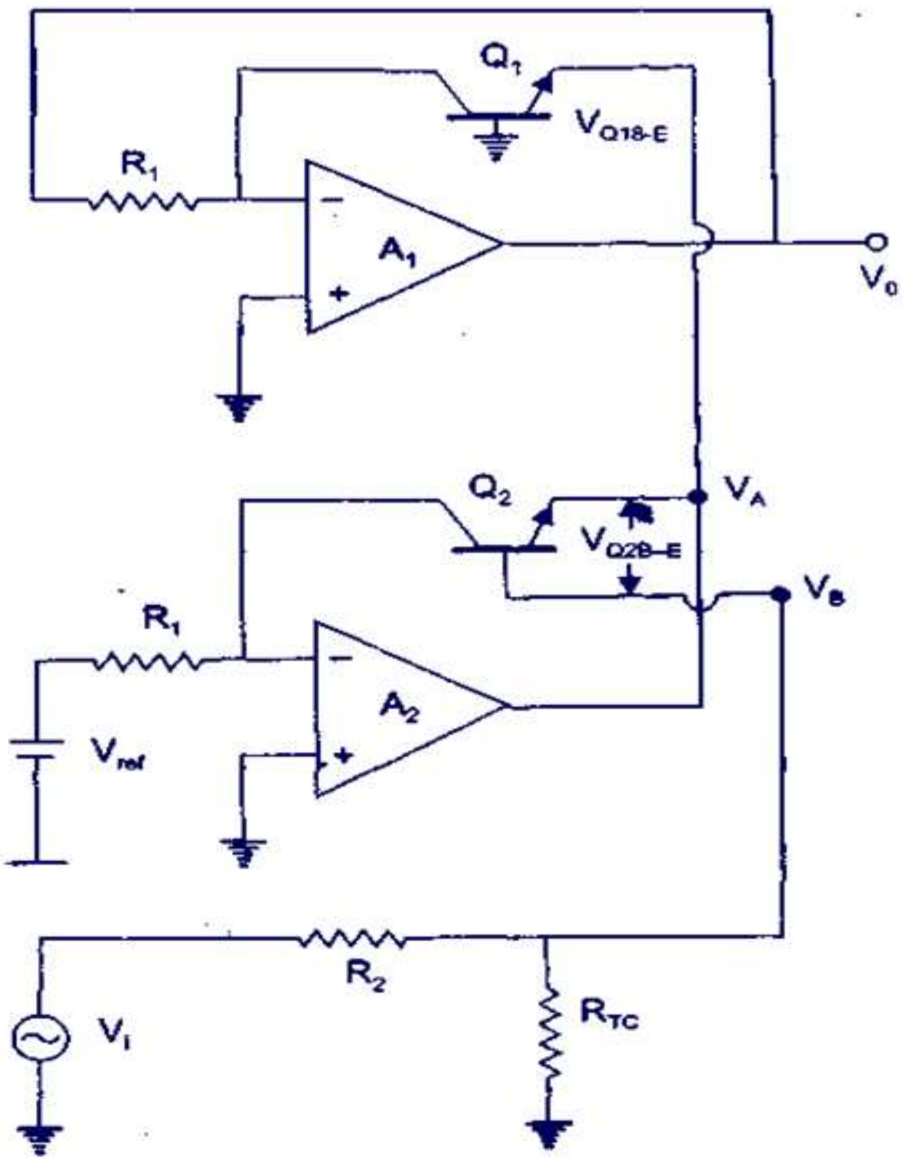
Basic Antilog Amplifier

Vin is converted in to current $I_c = I_{EBO}e^{Vin/K}$



$$V_{out} \cong -R_f I_{EBO} anti \ln\left(\frac{V_{in}}{0.025}\right)$$

- A transistor or a diode can be used as the input element.
- The operation of the circuit is based on the fact that $V_{out} = -R_f I_C$, and $I_C = I_{EBO}e^{Vin/K}$ where $K \cong 0.025$ V



Antilog amplifier

Antilog Amplifier

The circuit is shown in Fig. .The input V; for the antilog-amp is fed into the temperature compensating voltage divider R_2 and R_{TC} and then to the base of Q_2. The output V_o of the antilog-amp is fed back to the inverting input of A_1 through the resistor R_1. The base to emitter voltage of transistors Q_l and Q_2 can be written as

$$V_{Q1\ B\text{-}E} \approx \frac{kT}{q} \ln\left(\frac{V_o}{R_1 I_s}\right)$$

and

$$V_{Q2\ B\text{-}E} \approx \frac{kT}{q} \ln\left(\frac{V_{ref}}{R_1 I_s}\right)$$

Since the base of Q_1 is tied to ground, we get

$$V_A \approx -V_{Q1\ B\text{-}E} = -\frac{kT}{q} \ln\left(\frac{V_o}{R_1 I_s}\right)$$

$$V_B = \left(\frac{R_{TC}}{R_2 + R_{TC}}\right) V_i$$

The voltage at the emitter of Q_2 is

$$V_{Q2B\text{-}E} = V_B + V_{Q2\ E\text{-}B}$$

or,

$$V_{Q2B\text{-}E} = \left(\frac{R_{TC}}{R_2 + R_{TC}}\right) V_i - \frac{kT}{q} \ln\left(\frac{V_{ref}}{R_1 I_s}\right)$$

But the emitter voltage of Q_2 is V_A, that is,

$$V_A = V_{Q2B\text{-}E}$$

or,

$$-\frac{kT}{q} \ln \frac{V_o}{R_1 I_s} = \frac{R_{TC}}{R_2 + R_{TC}} V_i - \frac{kT}{q} \ln \frac{V_{ref}}{R_1 I_s}$$

or,

$$\frac{R_{TC}}{R_2 + R_{TC}} V_i = -\frac{kT}{q} \left(\ln \frac{V_o}{R_1 I_s} - \ln \frac{V_{ref}}{R_1 I_s}\right)$$

or, $$-\frac{q}{kT}\frac{R_{TC}}{R_2+R_{TC}}V_i = \ln\left(\frac{V_o}{V_{ref}}\right) \quad (4.51)$$

Changing natural log, i.e., ln to $\log_{10}$ using Eq. (4.38) we get

$$-0.4343\left(\frac{q}{kT}\right)\left(\frac{R_{TC}}{R_2+R_{TC}}\right)V_i = 0.4343\times\ln\left(\frac{V_o}{V_{ref}}\right) \quad (4.52)$$

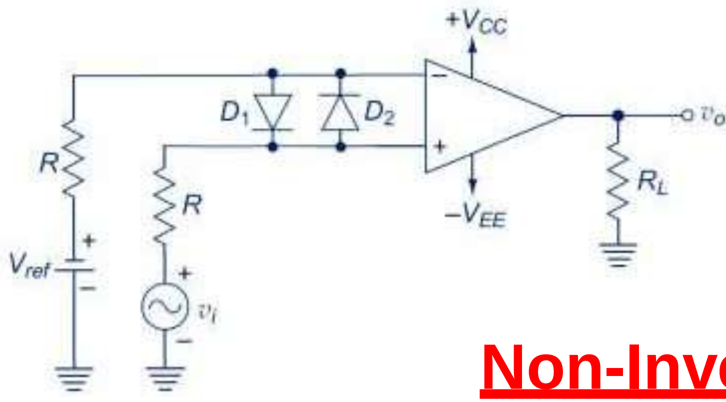
or, $$-K'V_i = \log_{10}\left(\frac{V_o}{V_{ref}}\right)$$

or, $$\frac{V_o}{V_{ref}} = 10^{-K'V_i}$$

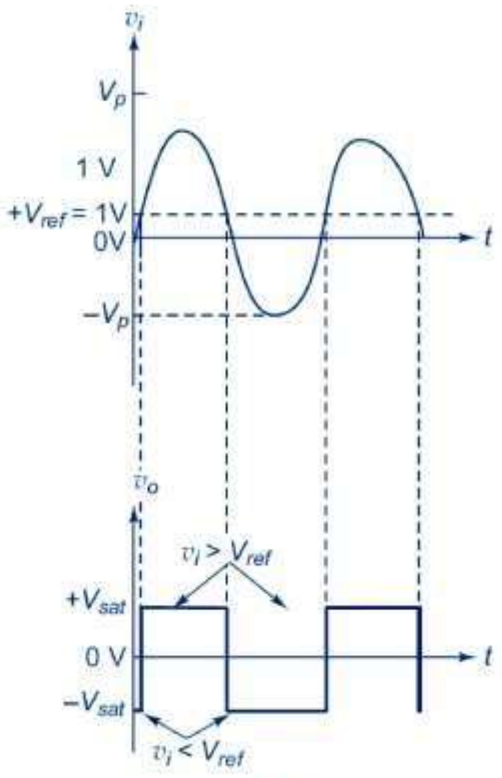
or, $$V_o = V_{ref}\,(10^{-K'V_i}) \quad (4.53)$$

where $$K' = 0.4343\left(\frac{q}{kT}\right)\left(\frac{R_{TC}}{R_2+R_{TC}}\right) \quad (4.54)$$

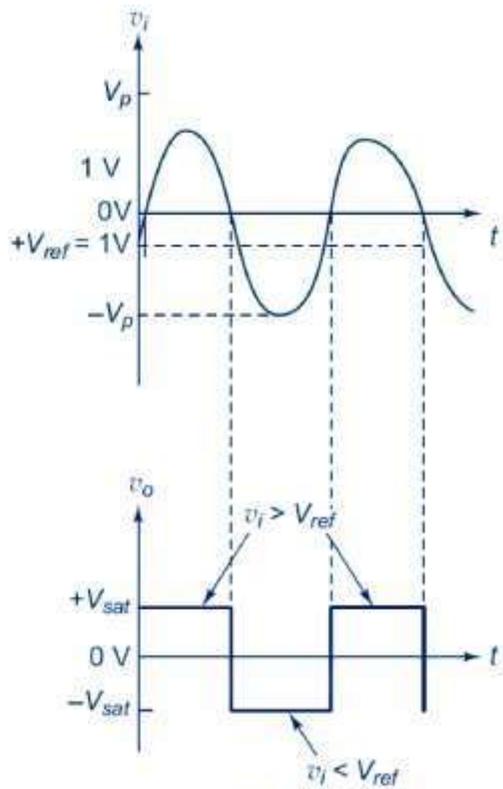
OP-AMP COMPARATORS



Non-Inverting Comparator.



(b)

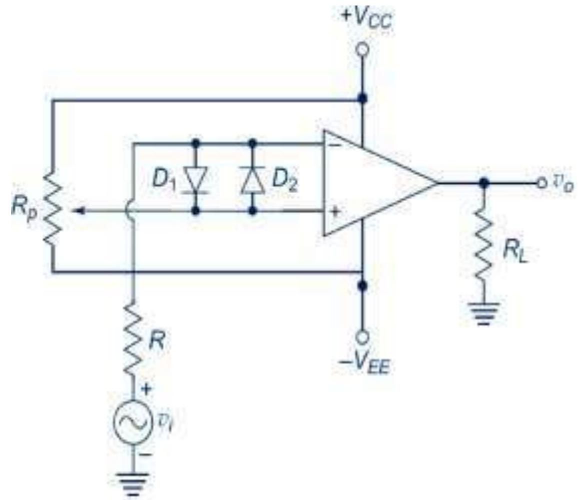


(c)

(b) Input and Output wave- forms when V_{ref} is +ve

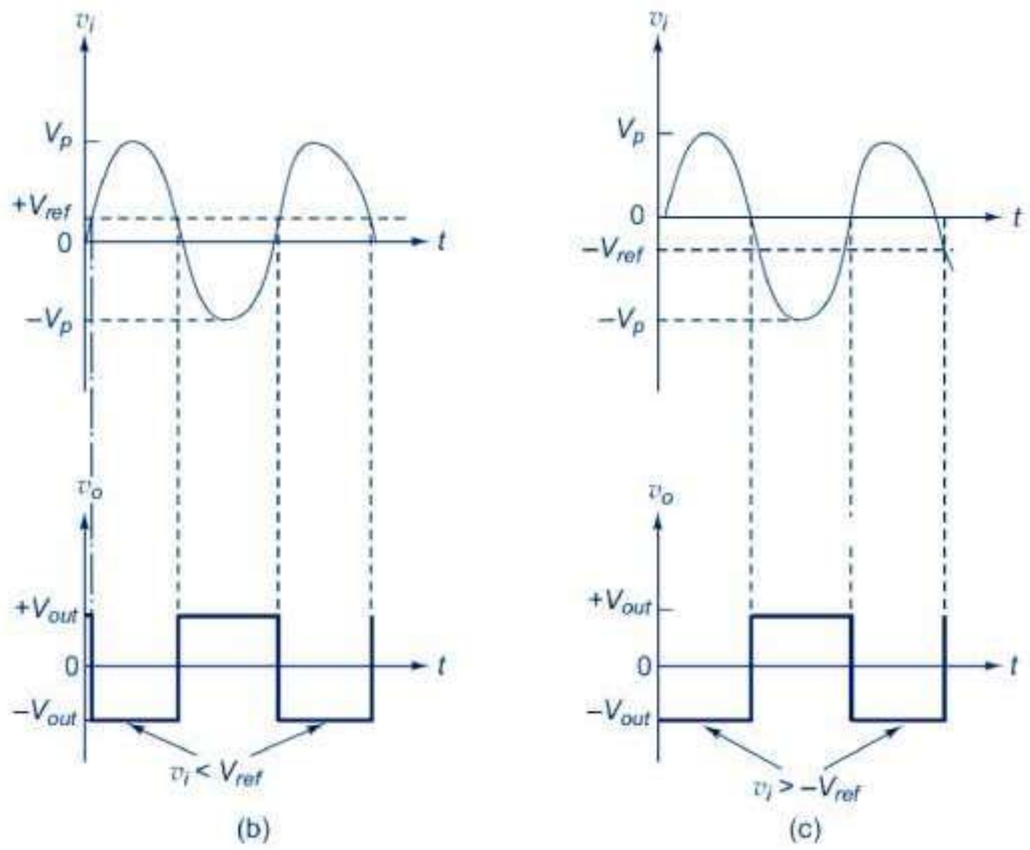
(c) Input and Output wave- forms when V_{ref} is -ve

Inverting Comparator.



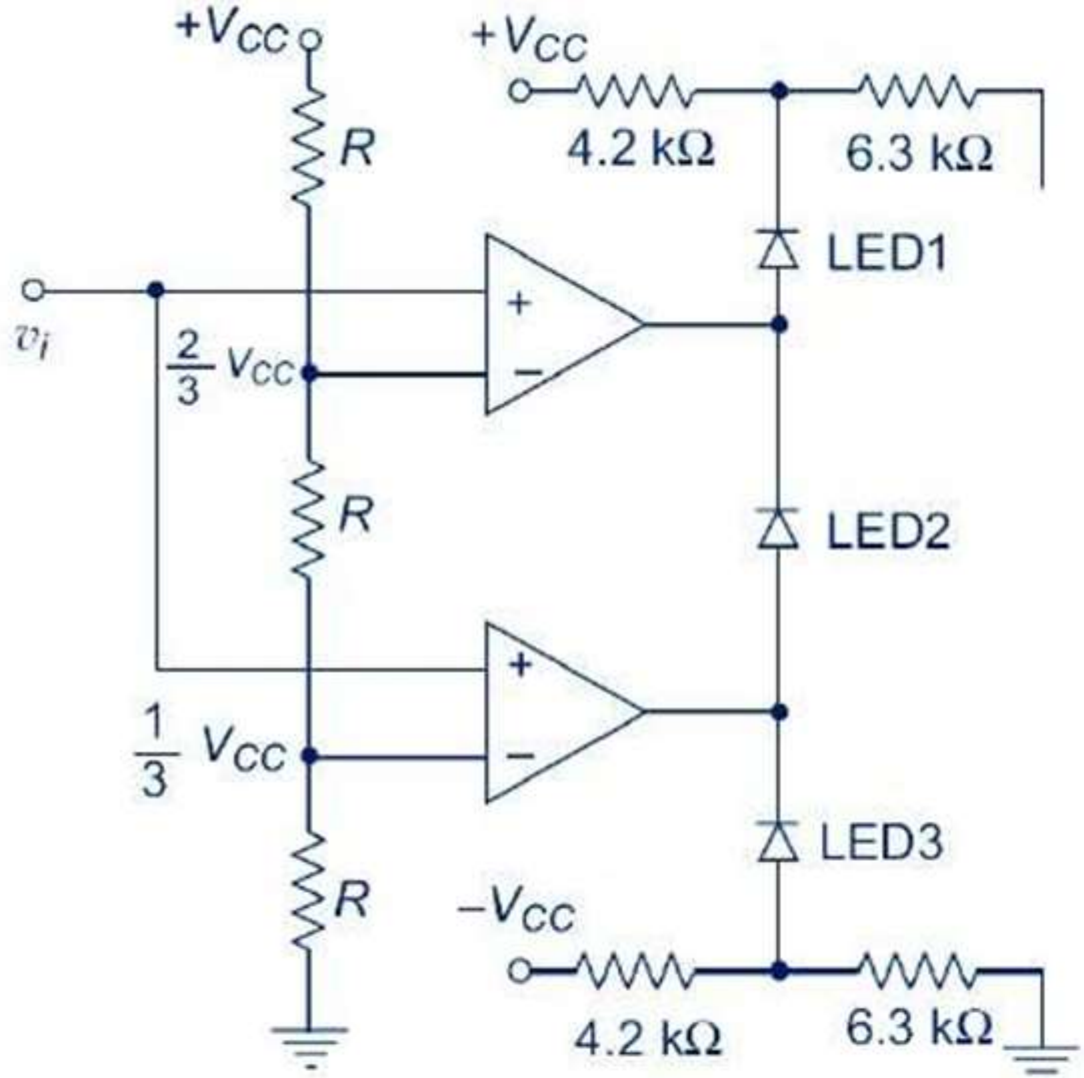
b) Input and Output Wave Forms when V_{ref} is +ve and

c) Input and Output Wave Forms when V_{ref} is –ve



WINDOW COMPERATOR

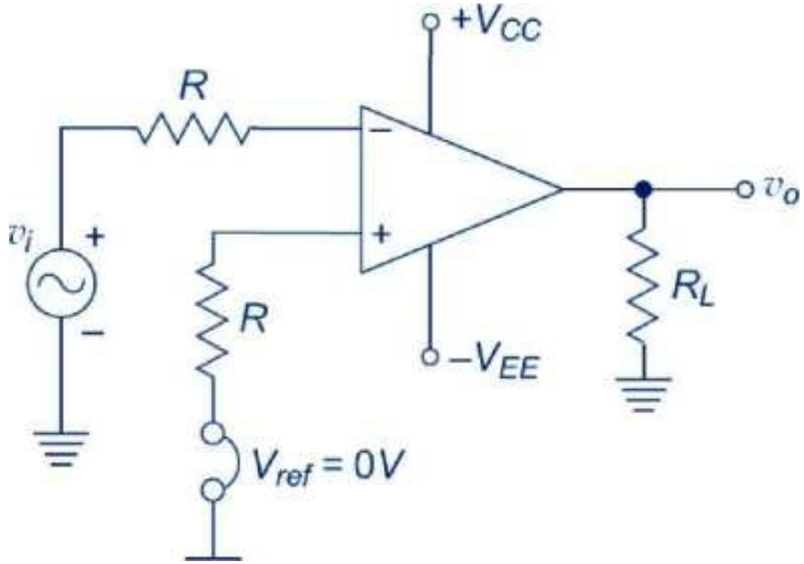
Used in A.C Voltage Stabilizers.



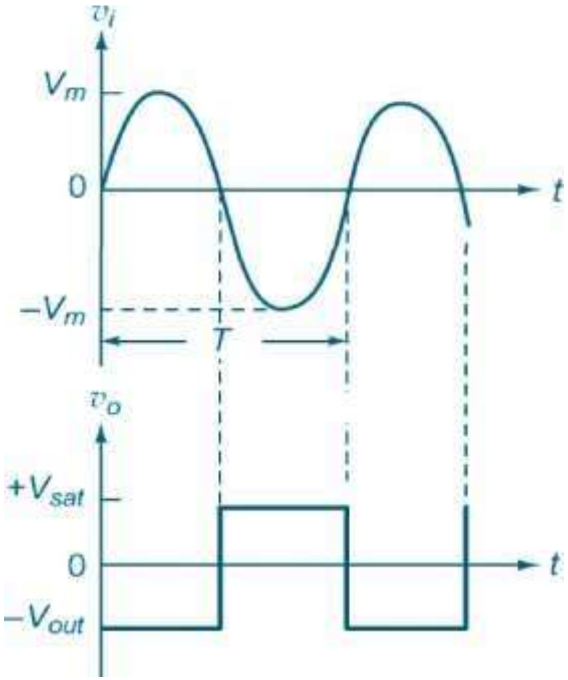
Three level comparator

If $V_{cc} = 6V$

Input(Volts)	LED3	LED2	LED1
Less than 2V	ON	OFF	OFF
Less than 4V & More than 2V	OFF	ON	OFF
More than 4V	OFF	OFF	ON



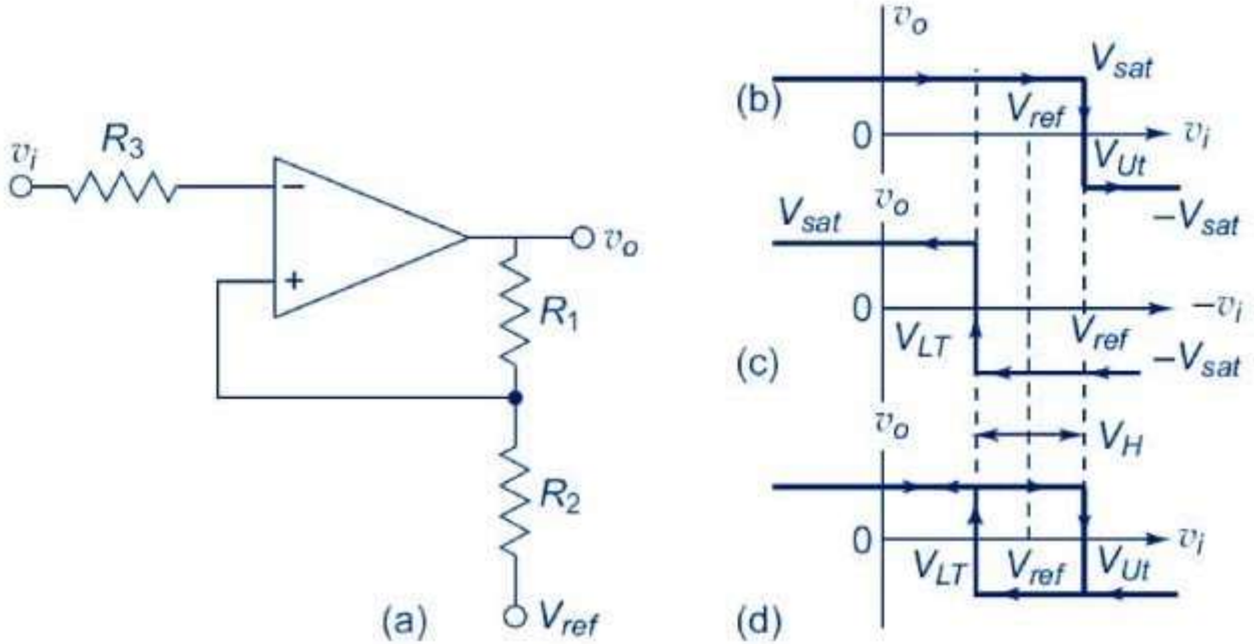
(a)



(b)

(a) Zero crossing detector and (b) Input and output waveforms

INVERTING SCHMITT TRIGGER



(a) Inverting Schmitt Trigger circuit (b)} (c) and (d) Transfer Characteristics of Schmitt Trigger

ZERO if V_{ref} is Zero.

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

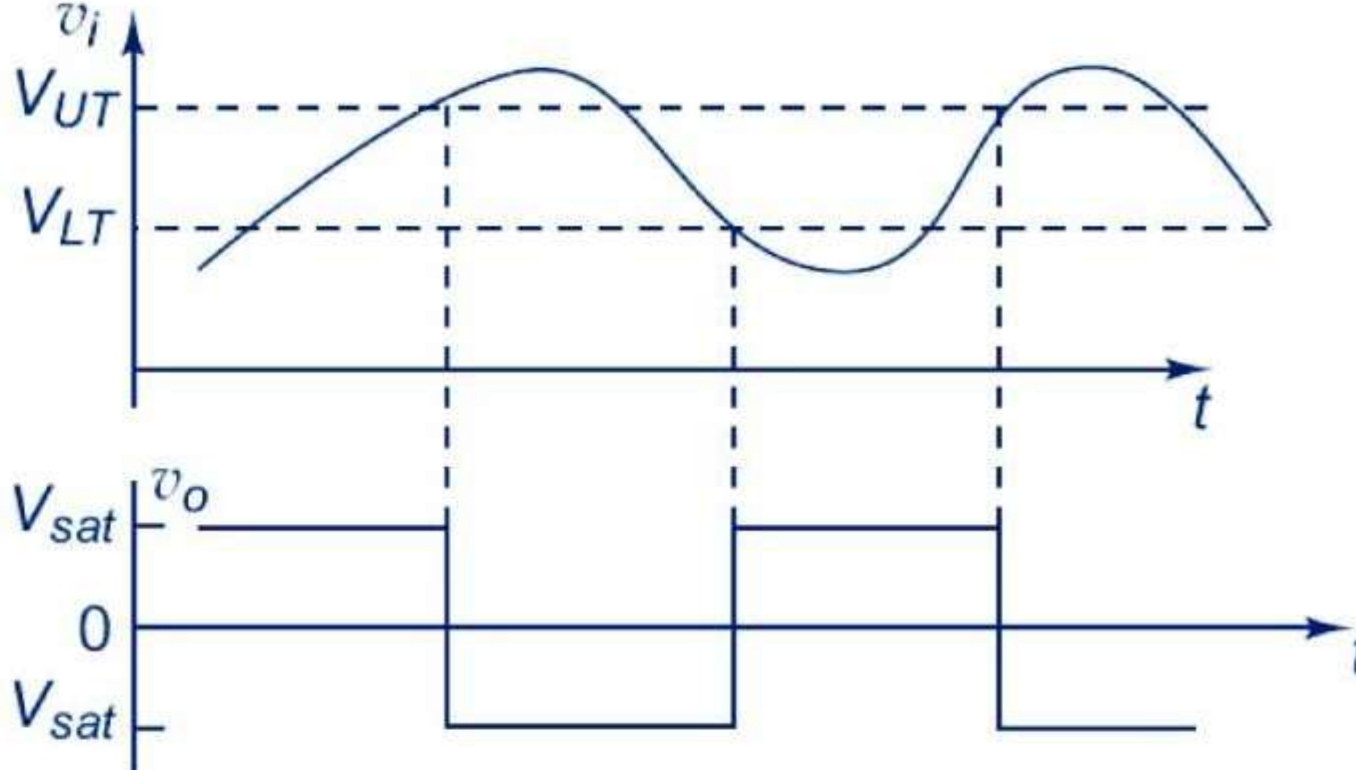
$$V_{LT} = \frac{V_{ref}R_1}{R_1 + R_2} - \frac{R_2 V_{sat}}{R_1 + R_2}$$

$$V_H = V_{UT} - V_{LT} = \frac{2R_2 V_{sat}}{R_1 + R_2}$$

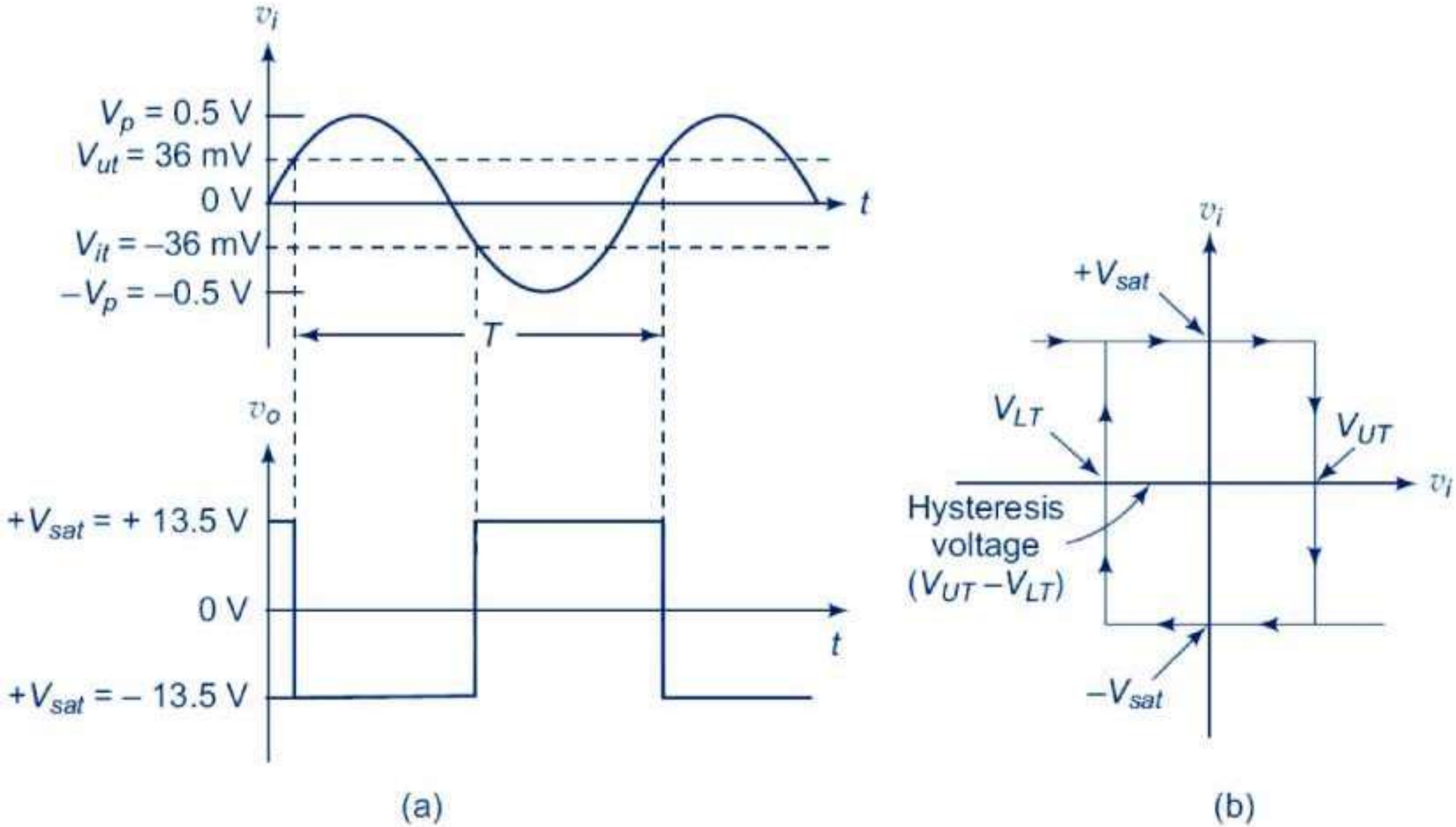
The input voltage v_i triggers the output v_o every time it exceeds certain voltage levels, V_{LT} & V_{UT} If $V_{ref} = 0$, then the voltage at the junction of R1 & R2 will form will determine V_{UT} & V_{LT} .

If $V_i < V_{LT}$, $V_o = +V_{sat}$

$V_i > V_{LT}$, $V_o = -V_{sat}$



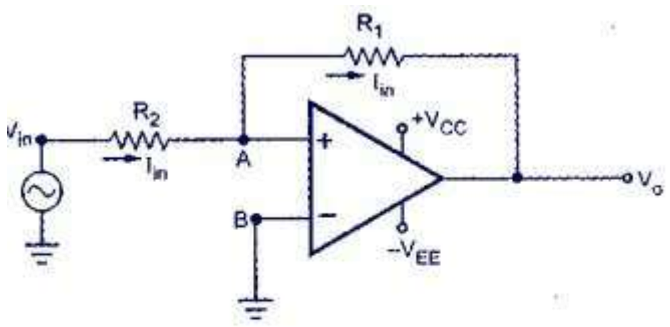
(e)

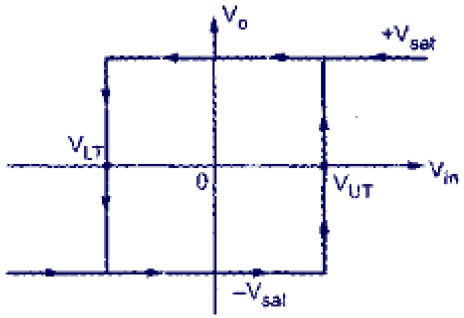


(a) Input and Output waveforms of Schmitt Trigger and (b) Output v_0 versus V_i plot of the hysteresis voltage.

If a sine wave frequency f=1/T is applied, a symmetrical square wave is obtained at the output. The vertical edge is shifted in phase by θ from zero crossover Where $\sin\theta = V_{UT}/V_m$ and V_m is the peak sinusoidal voltage.

NON-INVERTING SCHMITT TRIGGER





The input is applied to the non-inverting input terminal of the op-amp. To understand the working of the circuit, let us assume that the output is positively saturated i.e. at $+V_{sat}$. This is fedback to the non-inverting input through R_1. This is a positive feedback. Now though V_{in} is decreased, the output Continues its positive saturation level unless and until the input becomes more negative than V_{LT}. At lower threshold, the output changes its state from positive saturation $+ V_{sat}$ to negative saturation $- V_{sat}$. It remains in negative saturation till V_{in} increases beyond its upper threshold level V_{UT}.

Now V_A= voltage at point A $=I_{in}R2 = V_{UT}$

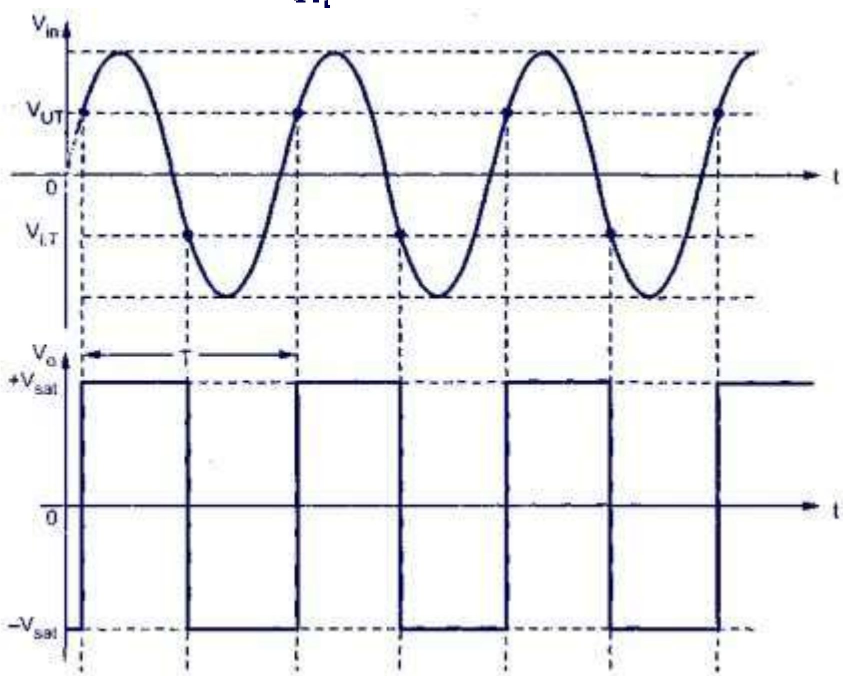
As op-amp input current is zero, I in entirely passes through R_1.

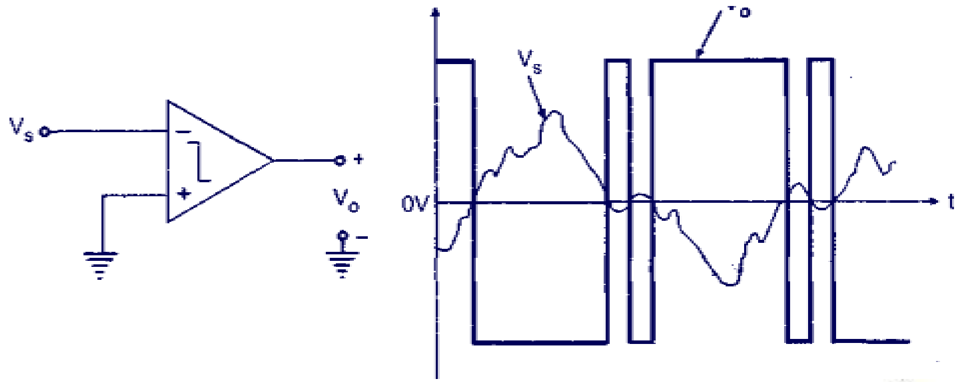
$$I_{in} = \frac{V_o}{R_1} = \frac{+V_{sat}}{R_1}$$

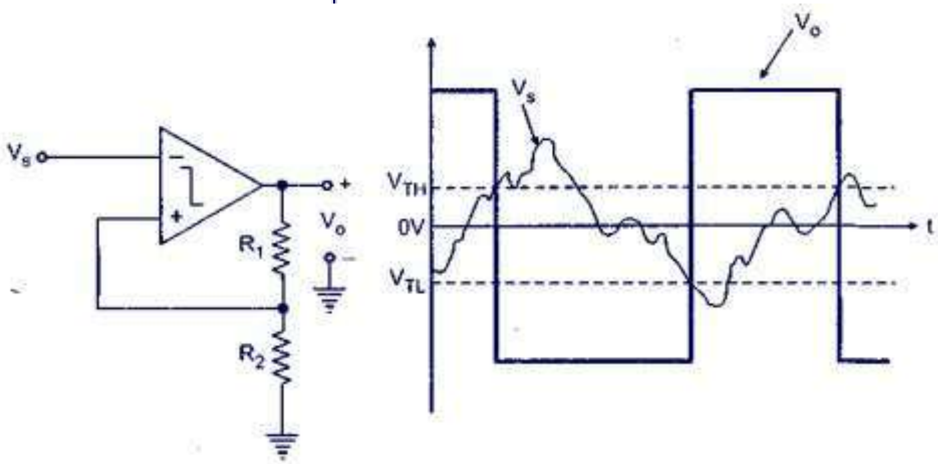
$$V_{UT} = I_{in} R_2 = \frac{R_2}{R_1}(+V_{sat}) = V_{sat}\frac{R_2}{R_1}$$

$$V_{LT} = \frac{R_2}{R_1}(-V_{sat}) = -V_{sat}\frac{R_2}{R_1}$$

$$H = V_{UT} - V_{LT} = 2V_{sat}\frac{R_2}{R_1}$$







Eliminates Comparator Chatter.

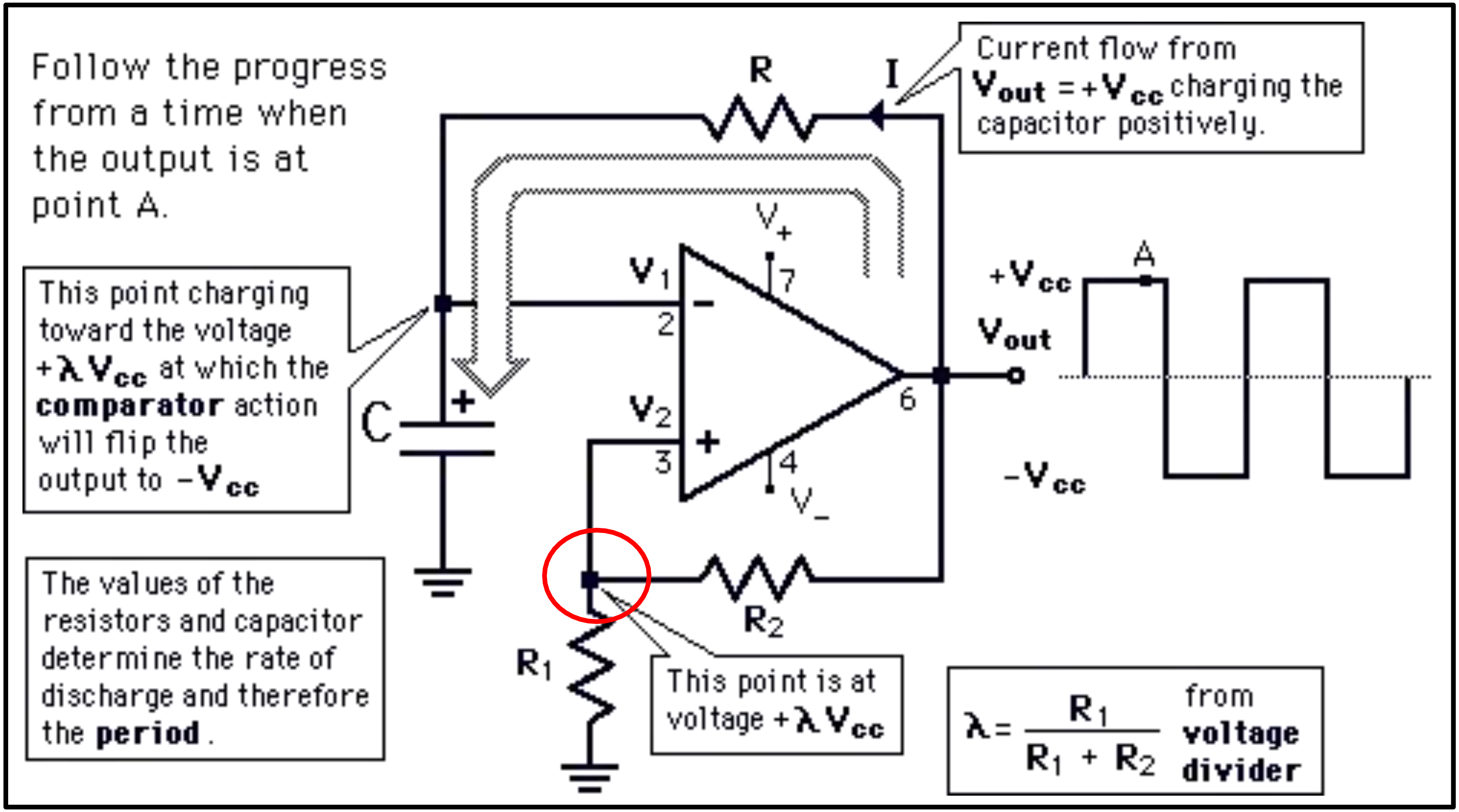
Chattering can be defined as production of multiple output transitions the input signal swings through the threshold region of a comparator. This is because of the noise.

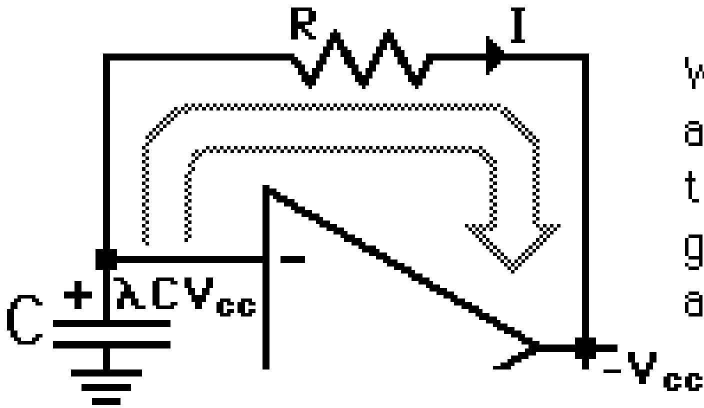
Comparison.

S.No.	Schmitt Trigger.	Comparator.
1.	The feedback is used.	No feedback is used.
2.	Op-amp is used in closed loop mode.	Used in open loop mode.
3.	No false triggering.	False Triggering.
4.	Two different threshold voltages exists as V_{UT} & V_{LT}	Single reference voltage V_{ref} or $-V_{ref}$.
5.	Hysteresis exists.	No Hysteresis exists.

Square & Triangular waveform generation

Square Wave Generator





When V_1 reaches $+\lambda V_{cc}$ then the switch to $-V_{cc}$ at the output occurs. The capacitor has charged to $+\lambda CV_{cc}$ and now begins to discharge. The general charging equation for a capacitor which already has an original charge is:

$$q = CV\left[1-e^{-t/RC}\right] + q_0\, e^{-t/RC}$$

For this case $V = -V_{cc}$ and $q_0 = \lambda CV_{cc}$ so the charging equation is

$$q = -CV_{cc}\left[1-e^{-t/RC}\right] + \lambda CV_{cc}e^{-t/RC}$$

Now when q gets to $-\lambda V_{cc}$ another switch will occur. This time is half the period of the square wave so it will be represented by T/2. At this time

$$-\lambda CV_{cc} = -CV_{cc}\left[1-e^{-T/2RC}\right] + \lambda CV_{cc}e^{-T/2RC}$$

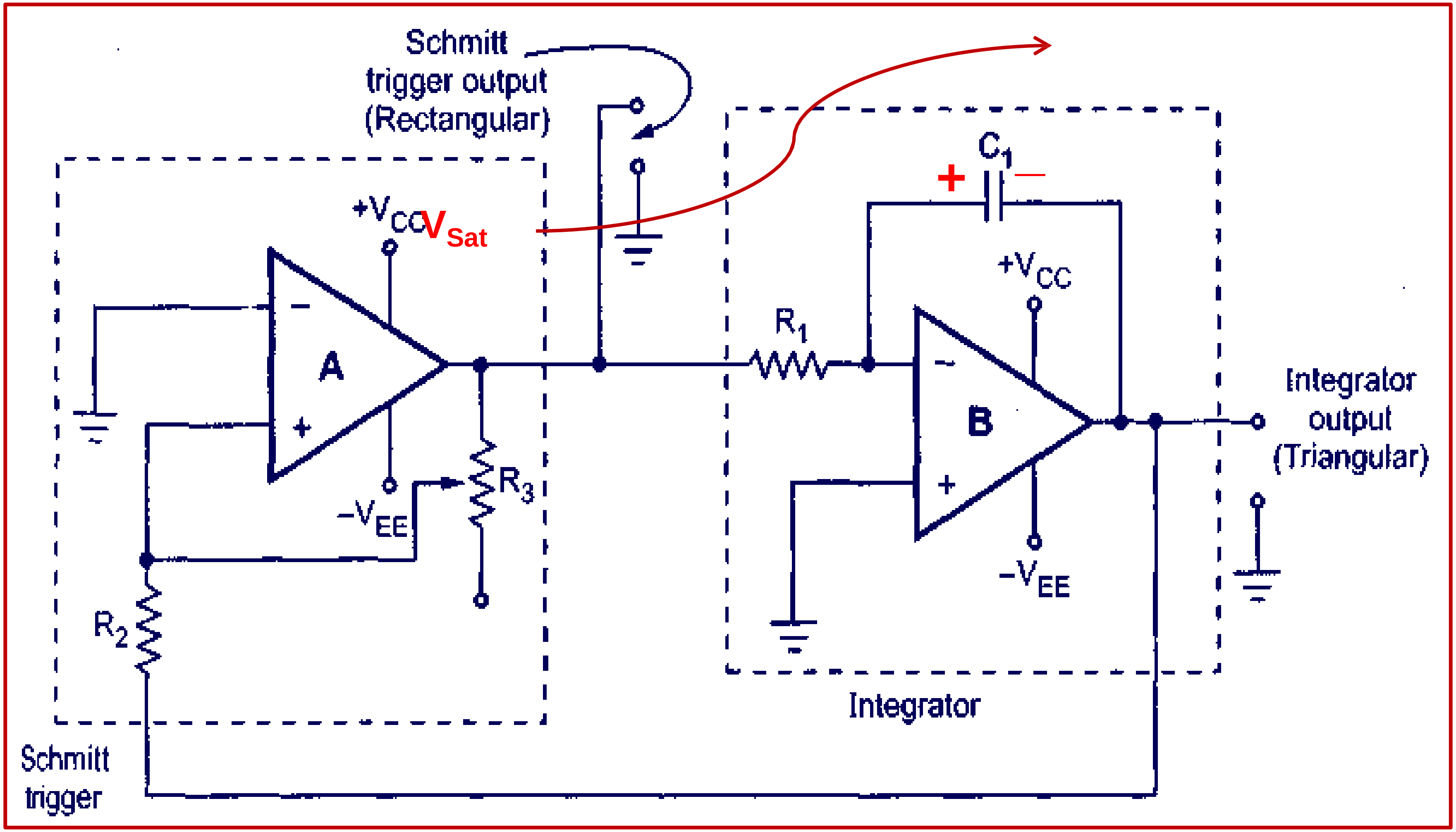
which when solved for T gives

$$T = 2RC\ \ln\left[\frac{1+\lambda}{1-\lambda}\right]$$

$V_{ref} = \beta V_{sat}$ **Where $\beta = R_2/(R_1+R_2)$**

Let V_0 initially be $+ V_{sat.}$ The capacitor charges through R to $+ \beta V_{sat}$. Then V_0 goes to $- V_{sat}$. The cycle repeats and output will be a Square Wave.

Triangular/rectangular wave generator.



Operation of the Circuit

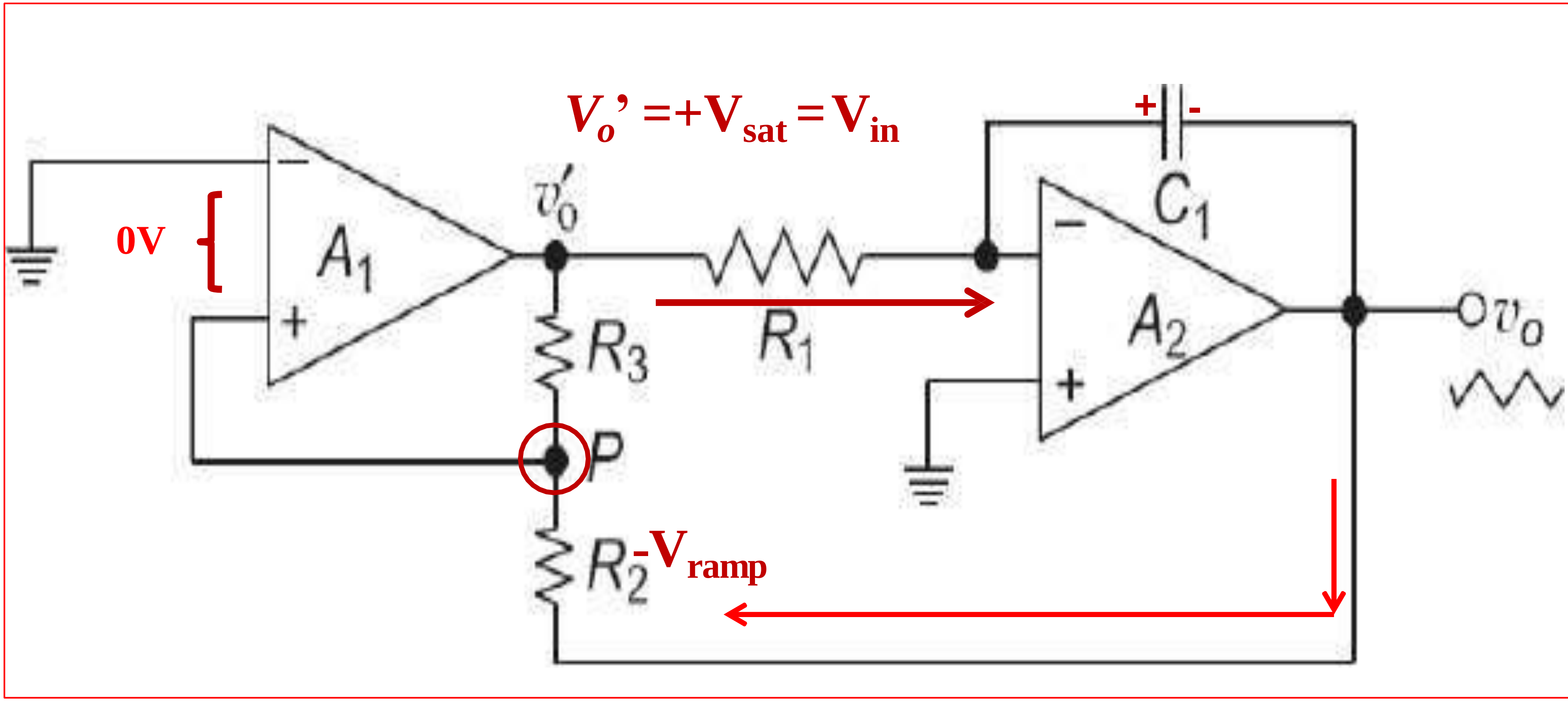
Let the output of the Schmitt trigger is + Vsat. This forces current + V_{sat}/R_1 through C_1, charging C_1 with polarity positive to left and negative to right. This produces negative going ramp at its output, for the time interval t_1 to t_2. At t_2 when ramp voltage attains a value equal to LTP of Schmitt trigger, the output of Schmitt trigger changes its stage from

+ V_{sat} to -V_{sat},

Now direction of current through C reverses. It discharges and recharges in opposite direction with polarity positive to right and negative to left. This produces positive going ramp at its output, for the time interval t_2 to t_3. At t_3 when ramp voltage attains a value equal to UTP of Schmitt trigger, the output of Schmitt trigger changes its state from - V_{sat} to + V_{sat} and cycle continues.

The circuit acts as free running waveform generator producing triangular and rectangular output waveforms.

$$f_o = \frac{1}{T} \qquad f_o = \frac{R_3}{4R_1R_2C_1}$$



$$\frac{v_o'}{R_3} = \frac{v_o}{R_2} \rightarrow (1)$$

$$+V_{Sat} = -V_{Sat}$$

$$+V_{ramp} = -V_{ramp}$$

$$v_o' = +V_{Sat}$$

$$V_o = -V_{Sat}$$

$$\frac{V_{Sat}}{R_3} = \frac{V_{ramp}}{R_2} \rightarrow (2)$$

$$V_{ramp} = \frac{R_2}{R_3}(-V_{sat}) \rightarrow (3)$$

$$V_{ramp} = \frac{R_2}{R_3}(-V_{sat}) \rightarrow (3)$$

$V_o(PP) = 2V_{ramp}$

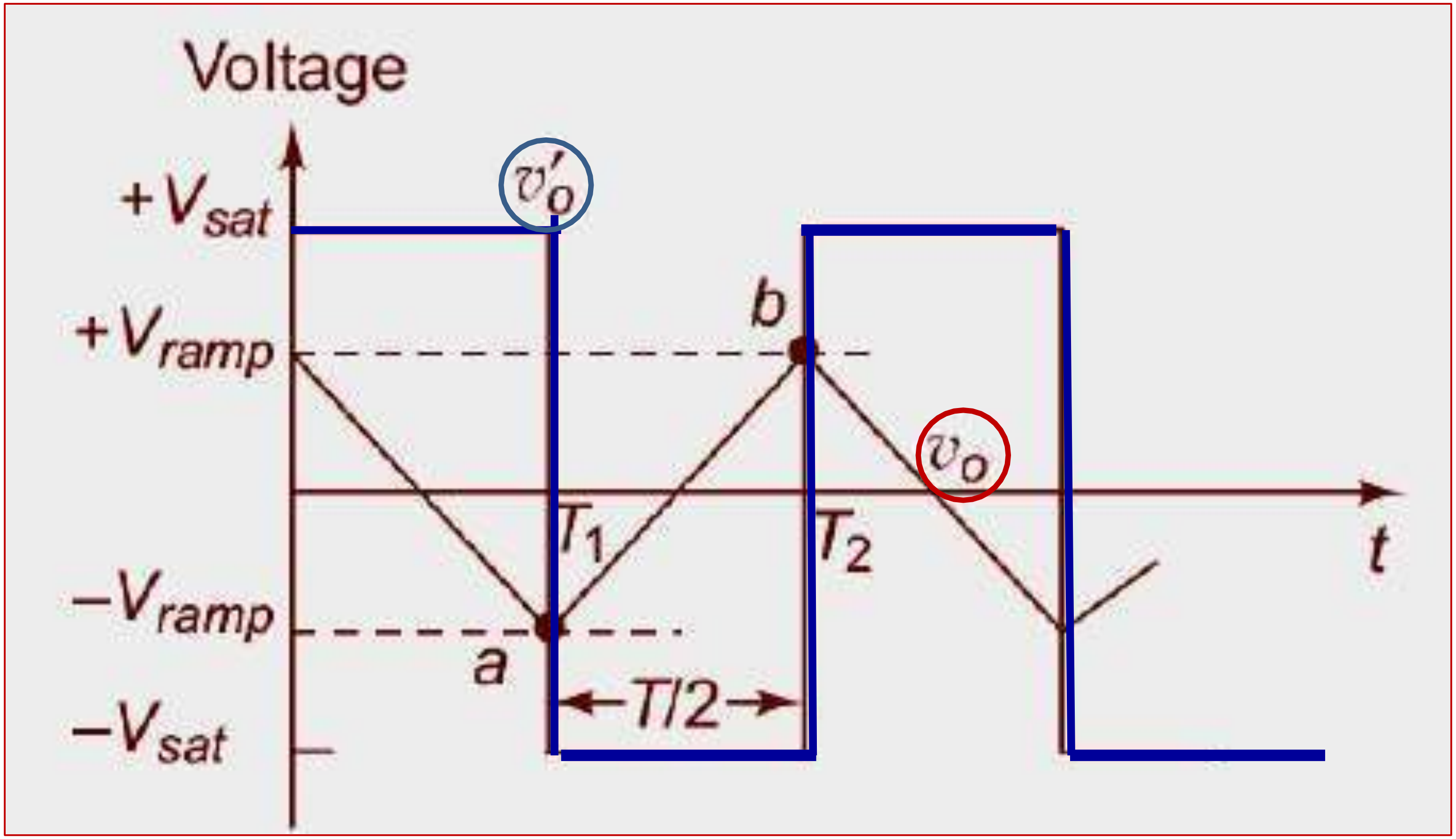
$$Peak\ to\ Peak\ of\ V_{ramp} = V_{(PP)} = 2\left(\frac{R_2}{R_3}\right)V_{sat} \rightarrow (4)$$

$V_{in} = V_{Sat}$

$$V_{o(pp)} = -\frac{1}{R_1C_1}\int_0^{T/2} -V_{sat}\,dt = \frac{V_{sat}}{R_1C_1}\frac{T}{2}$$

Substitute $V_{(pp)}$ from Eqn. (4)

$$T = \frac{2V_{o(pp)}R_1C_1}{V_{sat}} \qquad f_o = \frac{1}{T} = \frac{R_3}{4R_1R_2C_1}$$



Voltage
$+V_{sat}$
v_o'
$+V_{ramp}$
b
v_o
T_1
T_2
t
$-V_{ramp}$
a
T/2
$-V_{sat}$