Triggering of Bistable Multivibrator

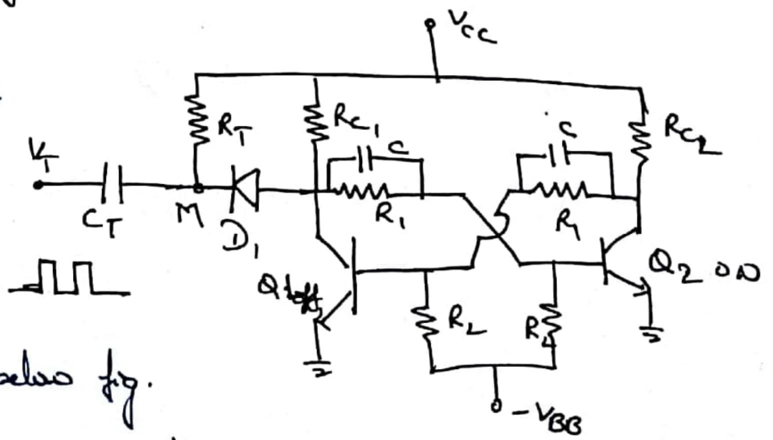
A negative pulse of short duration is applied suitably to the collector of the OFF transistor to cause triggering.

- ↳ Unsymmetrical triggering (or) Asymmetrical triggering
- ↳ Symmetrical triggering

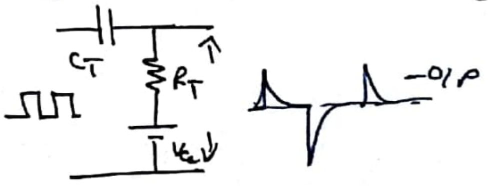
The normal practice is to apply the triggering pulse at the output i.e collector terminal of the OFF transistor. Additionally the applied pulse is a negative pulse of short duration (or) a negative - going step voltage. The pulse is applied through a RC highpass i.e differentiator ckt:

Asymmetrical Triggering :-

C_T & R_T together constitute a differentiator ckt & when a pulse is applied as i/p to such ckt & o/p is in spikes as in below fig.



These voltage spikes are alternately positive & negative w.r.to V_{CC} as is evident from the o/p form.

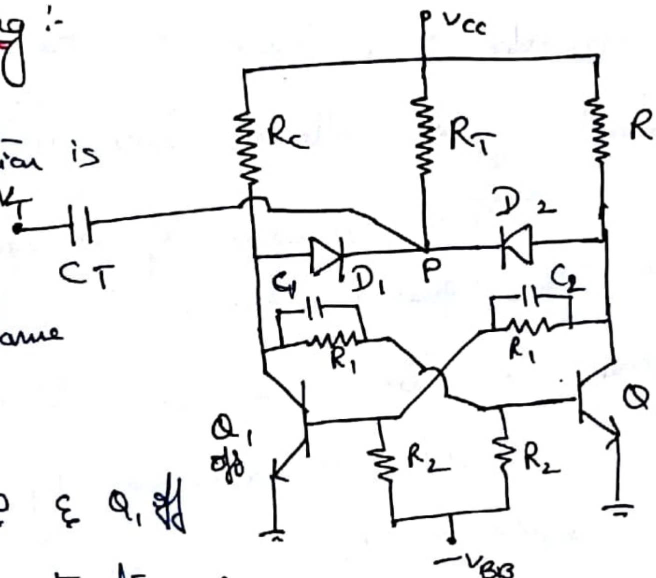


It is seen that D_1 can transmit only negative spikes. A negative spike appearing at M is transmitted through the commutating capacitor C_1 & it appears at the base of Q_2 ON. As a result, the base of Q_2 goes negative & gets OFF.

If continuous triggering of binary in both direction is required, => Asymmetrical binary triggering requires two triggering pulses from two separate sources.

Symmetrical Triggering :-

Triggering in either direction is effected by means of pulses obtained from the same source.



Let it be Q_2 ON & Q_1 off

Since Q_2 is ON i.e in saturation $V_D = V_{CE(sat)} = 0$

Hence the supply voltage V_{CC} which is positive & both diodes in reverse bias.

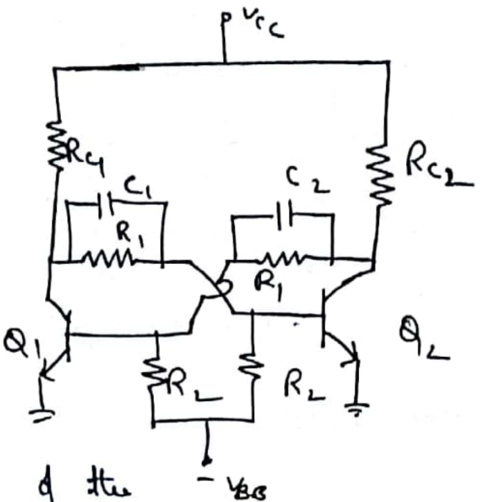
When a negative triggering pulse appears at P, Diode D_1 gets forward biased & conducts. Hence the negative spike gets applied at C. It is transmitted through capacitor C_1 & it appears at the base of Q_2. The result of it is that the base of Q_2 goes negative & Q_2 gets off & Q_1 gets ON.

Thus with pulses obtained from the same triggering source, triggering of the binary in either direction is effected.

Commutating Capacitors :-

[Speed-up Capacitors (or)

Transpose Capacitors]



Let Q_2 be ON & Q_1 OFF

In order to change the state of the binary, a negative spike voltage is applied to the collector of the OFF transistor Q_1. Since the base of Q_2 goes negative, the potential of its collector terminal 'D' rapidly rises.

This increases of voltage at the collector of Q_2 must be quickly transmitted to the base of Q_1 so as to change its state from OFF to ON, as quickly as possible.

This is achieved by providing a suitable capacitor C_2 across R_1.

Resistors R_1, R_2 & capacitor C_2 & C_1 together constitute a perfectly compensated attenuator.

The main feature of the commutating capacitors is that they reduce the transition time & increase the switching speed. Hence the name speed-up capacitor. The smallest permissible interval between two successive triggers is termed as the resolving time of the flip flop

$$C_1 = C_2 = \frac{1}{2.3 f_{max} (R_1 || R_2)}$$

f_{max} = max triggering freq

→ The smallest allowable interval between triggers is called the resolving time

The voltage across the commutating capacitors C_1 & C_2 need not change during this transfer of conduction. After this transfer of condition, the capacitors are allowed to interchange their voltages.

This additional time required for the purpose of completing the recharging of capacitors after the transfer of conduction is called the setting time.

Transition time :- the time taken for the transfer of conduction from one device to another is called transition time.

Resolution time :- Sum of transition time & setting time.

Methods of improving resolution :-

1. By reducing all stray capacitances :- Reductions in the values of stray capacitances reduce their charging time, resulting in the time taken by the transistors to go to the opposite state.

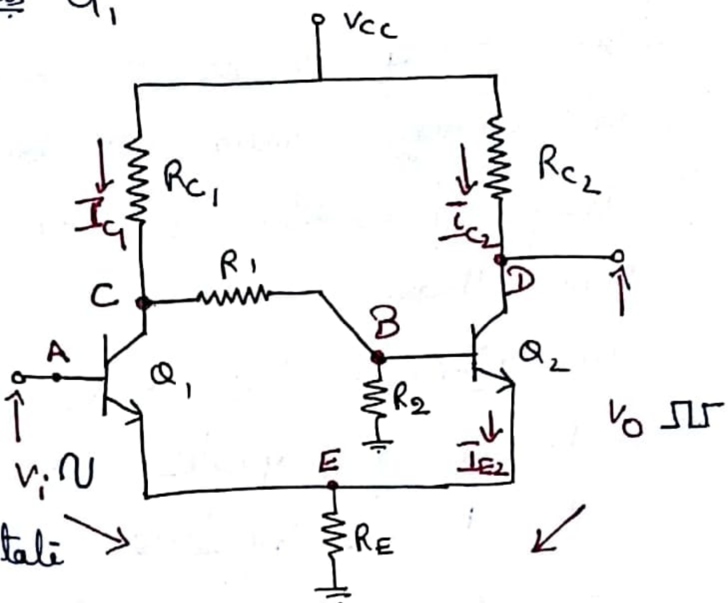
2. By reducing the resistors R_1, R_2 & R_C :- Reductions in the values of R_1 & R_2 result in a reduction in the charging time of the commutating capacitors with a consequent improvement in transition speed. Reducing resistors also reduces the recovery time.

3. By not allowing the transistors to go into saturation :- When the transistors do not saturate, the storage time will be reduced resulting in fast change from ON to OFF.

Schmitt trigger :- Emitter - Coupled binary

Let the i/p for the Trans^r Q_1 be a sinusoidal voltage

$V_i = V_m \sin\omega t$



when $V_i = 0$

the Q_1 gets off & at C pt we get V_{cc} which makes the Q_2 conduction state but in active region.

Let I_{C_2} denote the Q_2 current.

assuming $i_{e_2} = i_{C_2}$ $\Rightarrow$ $V_E = i_{C_2} R_e \rightarrow (1)$

if V_i rises to that voltage where the Q_1 can be get conduction $\Rightarrow (V_E + V_\gamma)$ where $V_\gamma \Rightarrow$ cut-in voltage of Q_1

$\because$ if $V_i < V_E + V_\gamma \Rightarrow Q_1$ off & if $V_i = V_E + V_\gamma$ the Q_1 gets ON $\Rightarrow V_i = V_E + V_\gamma$

$\Rightarrow V_i = i_{C_2} R_e + V_\gamma$

which are called as upper triggering point UTP where if $V_i >$ UTP then Q_2 gets off & Q_1 gets ON

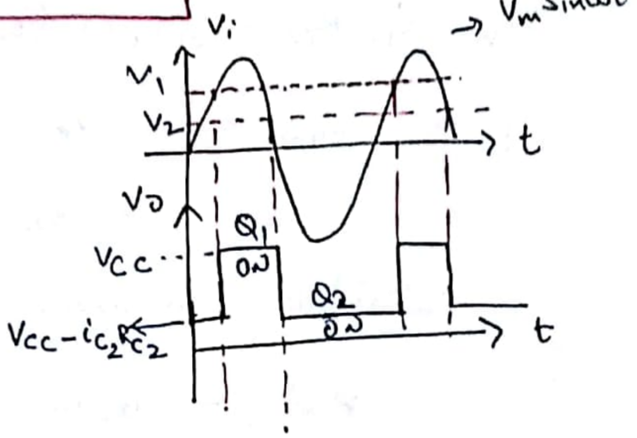
As V_i decreases i.e. V_A decreases the potential of pt. C progressively increases & eventually when V_B becomes equal to

$$V_B = V_{BE(act)} + V_E$$

where Q_2 gets ON again & Q_1 gets off. which is called as Lower triggering point LTP (or) V_2

$$V_2 = V_{BE(act)} + i_{c_1} R_e \quad \text{where } V_E = i_{c_1} R_e$$

$$\boxed{\begin{aligned} UTP &= V_1 = V_\gamma + i_{c_2} R_e \\ LTP &= V_2 = V_{BE(act)} + i_{c_1} R_e \end{aligned}}$$



Si $\rightarrow V_\gamma = 0.5V$

$V_{BE}(act) = 0.6V$

$V_{BE}(sat) = 0.7V$

Ge $\rightarrow V_\gamma = 0.1$

$V_{BE}(act) = 0.2V$

$V_{BE}(sat) = 0.3V$

Evaluation of V_1 (UTP) & (LTP) V_2 :-

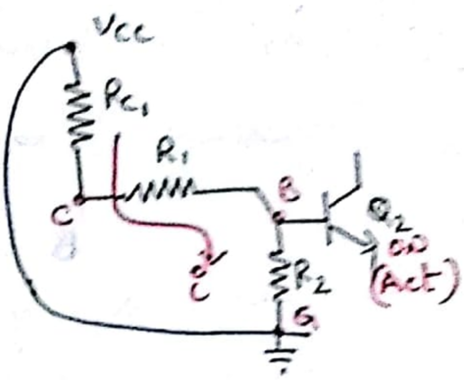
↳ (i) UTP $\Rightarrow (V_1)$ Upper Triggering point

Q_1 is off & Q_2 conductions & we know

$$V_1 = V_\gamma + i_{c_2} R_e$$

Now let us find i_{c_2} & i_{B_2} of Q_2. By applying Thevenin equivalent ckt at pt B.

At point B :-



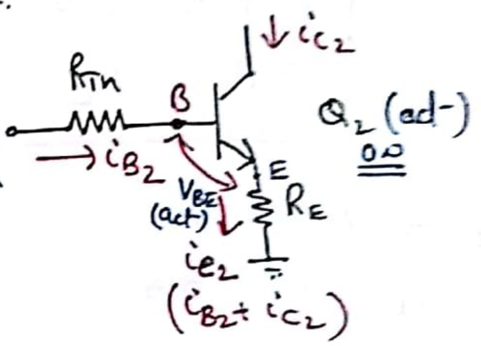
$(V_B) = V_{Th} = i R_2$

where $i = \dfrac{V_{CC}}{R_{C_1} + R_1 + R_2}$

$\Rightarrow V_{Th} = \dfrac{V_{CC} \cdot R_2}{R_{C_1} + R_1 + R_2}$

& $R_{(B pt)} = R_{Th} = R_2 \| (R_{C_1} + R_1) = \dfrac{R_2(R_{C_1} + R_2)}{R_{C_1} + R_2 + R_1}$

$\Rightarrow$ Apply KVL to the loop, we get-



$V_{Th} - i_{B_2} R_{Th} - V_{BE(act)} - (i_{B_2} + i_{C_2}) R_e = 0$

in the active region $h_{fe} = \dfrac{i_{C_2}}{i_{B_2}}$

$i_{C_2} = h_{fe}\, i_{B_2}$

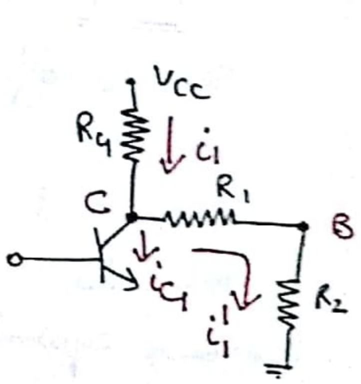
Substituting in above loop eqn we get

$V_{Th} - i_{B_2} R_{Th} - V_{BE(act)} - i_{B_2}(1 + h_{fe}) R_e = 0$

$\Rightarrow i_{B_2} = \dfrac{V_{Th} - V_{BE(act)}}{R_{Th} + R_e(1 + h_{fe})}$ $\quad \because i_{C_2} = h_{fe}\, i_{B_2}$

Now we get $V_1 = V_\gamma + i_{C_2} R_e$

To evaluate LTP (V_2)



where Q_1 is ON & Q_2 gets off

$\Rightarrow V_B = i_1' R_2$ (w.r.to gnd)

where $i_1' = \dfrac{V_C}{R_1 + R_2}$

$\Rightarrow V_B = \dfrac{V_C \cdot R_2}{R_1 + R_2}$

Let us assume $m = \dfrac{R_2 + R_1}{R_2}$

$\Rightarrow V_B = \frac{1}{m} \cdot V_C \Rightarrow \underline{\underline{V_C = m V_B}}$

But from the ckt $i_{c_1} = i_1 - i_1'$

where $i_1 = \dfrac{V_{cc} - V_c}{R_{c_1}}$; $i_1' = \dfrac{V_B}{R_2}$

$$i_{c_1} = \frac{V_{cc} - mV_B}{R_{c_1}} - \frac{V_B}{R_2}$$

As we know that V_2

$$V_2 = V_{BE(act)} + i_{c_1} R_e$$

when by sub i_{c_1} we get

$$V_2 = V_{BE}(act) + \left\{\frac{V_{cc} - mV_B}{R_{c_1}} - \frac{V_B}{R_2}\right\} R_e$$

But $V_2 = V_B = LTP$

$$\Rightarrow V_B = V_{BE}(act) + \left\{\frac{V_{cc} - mV_B}{R_{c_1}} - \frac{V_B}{R_2}\right\} R_e$$

$$V_B\left[1 + \frac{mR_e}{R_{c_1}} + \frac{R_e}{R_2}\right] = V_{BE}(act) + \frac{V_{cc} R_e}{R_{c_1}}$$

$$\Rightarrow V_B = \frac{V_{BE}(act) + \left(\frac{V_{cc} \cdot R_e}{R_{c_1}}\right)}{1 + \frac{mR_e}{R_{c_1}} + \frac{R_e}{R_2}} = V_2 = LTP$$

Designing of Schmitt trigger :-

↳ ① $\boxed{R_1 = 3R_{C_1}}$

↳ ② R_S is usually taken as far as less than the Product $h_{fe} \cdot R_e$ i.e $R_S << h_{fe} R_e$

↳ ③ for evaluating R_{C_2}

$$V_{CE(Q_2)} = \frac{V_{CC}}{3}$$

Problem.

① Design a schmitt trigger ckt n-p-n transistor for following specifications $V_{CC} = 12V$; $UTP = 3.5V$ $LTP = 2.5V$ $h_{fe} = 50$ $i_{C_2} = 2mA$.

note → ① with Q_2 Conducting in the active region & Q_1 off

$$UTP = V_\gamma + V_{E_2}$$

$$UTP = V_\gamma + i_{C_2} R_e$$

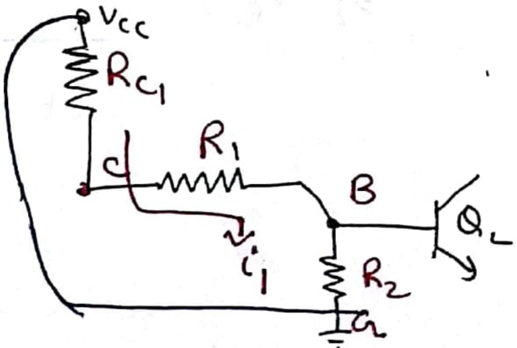
$$R_e = \frac{UTP - V_\gamma}{i_{C_2}} = \frac{3.5 - 0.5}{2m} = 1.5k\Omega$$

As per designing rules $R_S << h_{fe} R_e$

$$R_S << (50)(1.5k) = 75k\Omega$$

$$R_S << 1k\Omega \text{ or } 2k\Omega$$

To find R_{C_1} :-



$$V_{in(B)} = i_1 R_2$$

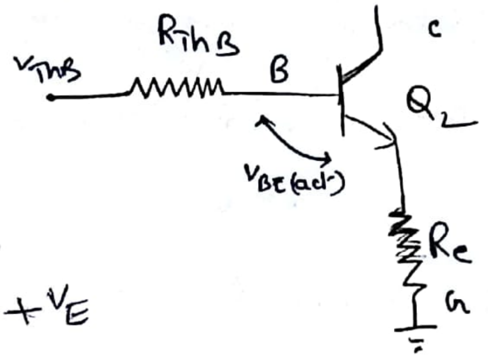
where $i_1 = \dfrac{V_{CC}}{R_{C_1} + R_1 + R_2}$

$$V_{in(B)} = \frac{V_{CC} R_2}{R_{C_1} + R_1 + R_2}$$

$$R_{Th(B)} = (R_{C_1}+R_1) \,\|\, R_2 = \frac{(R_{C_1}+R_1)\,R_2}{R_{C_1}+R_1+R_2}$$

$$V_{Th(B)} - i_{B_2}R_{Th(B)} - V_{BE(act)} - V_E = 0$$

$i_{B_2}R_{Th(B)}$ Can neg.



$$\Rightarrow V_{Th} - V_{BE(act)} - V_E = 0$$

$$\Rightarrow \frac{V_{CC}R_2}{R_{C_1}+R_1+R_2} = V_{BE(act)} + V_E$$

$$\Rightarrow \frac{R_2}{R_{C_1}+R_1+R_2} = \frac{V_{BE(act)}+V_E}{V_{CC}} = \frac{0.6+(UTP-V_\gamma)}{12V}$$

$$\Rightarrow \frac{R_2}{R_{C_1}+R_1+R_2} = \frac{3.6}{12} = 0.3 \quad ---(1)$$

with Q_2 off & Q_1 Conducting :-

$$LTP = V_2 = \frac{V_{BE(act)} + \frac{V_{CC}R_e}{R_{C_1}}}{1+\left[\frac{R_1+R_2}{R_2}\right]\frac{R_e}{R_{C_1}} + \frac{R_e}{R_2}} = \frac{V_{BE(act)} + \frac{V_{CC}R_e}{R_{C_1}}}{1+\frac{R_e}{R_{C_1}}\left[\frac{R_{C_1}+R_1+R_2}{R_2}\right]}$$

$$2.5 = \frac{0.6R_{C_1}+18}{R_{C_1}+5} \qquad \text{as we know } \frac{R_{C_1}+R_1+R_2}{R_2} = \frac{1}{0.3}$$

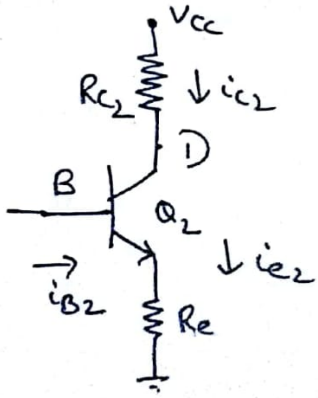
$$2.5R_{C_1} - 0.6R_{C_1} = 18 - 12.5 \Rightarrow R_{C_1} \simeq \underline{\underline{2.9}}$$

To find R_1 :- $\Rightarrow R_1 = 3R_{C_1} = 8.7k\Omega$

To find R_2 :- $\frac{R_2}{R_{C_1}+R_1+R_2} = 0.3 \Rightarrow R_2 = 4.97k\Omega$

To find R_{C_2} :- $V_{CE(Q_2)} = \frac{V_{CC}}{3}$

Apply KVL to D-E loop



$$V_{CC} - i_{C_2}R_{C_2} - V_{CE(Q_2)} - i_{E_2}R_e = 0$$

$$\underline{R_{C_2} = 2.5k\Omega}$$

Hysteresis :-

Let us Consider an example :-

A Schmitt trigger has following specifications

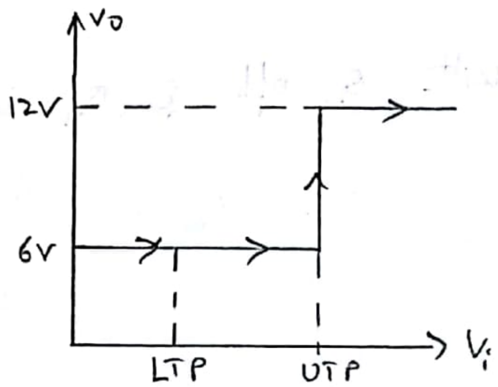
$V_{cc} = 12V$; $UTP = 5V$; $LTP = 3V$ & $I_c = 3mA$ &

$R_{C_1} = R_{C_2} = 2k\Omega$

Case ① => when Q_2 ON & Q_1 is off

$$V_D = V_0 = V_{cc} - i_{c_2} R_{C_2} = 12 - 3m \times 2k = 12 - 6$$
$$= 6V$$

when Q_2 off => $i_{c_2} = 0$ then $V_D = V_{cc} = 12V$



=> when V_i is 0 then

UTP = 4V there Q_2 is ON

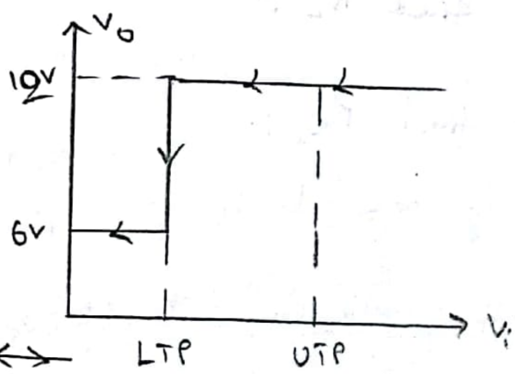
& when V_i = UTP then Q_1 begins

to on then $V_0 = V_{cc}$

Case ② => As V_i > UTP there Q_1 ON & Q_2 off

at V_i = LTP the o/p instantly falls to 4V &

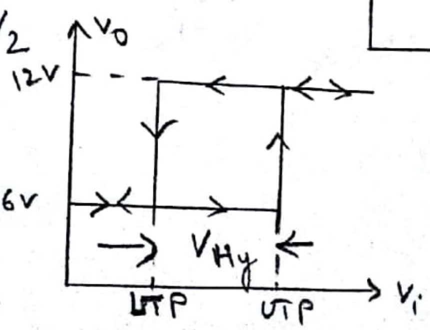
remains at that level until V_i again becomes zero.



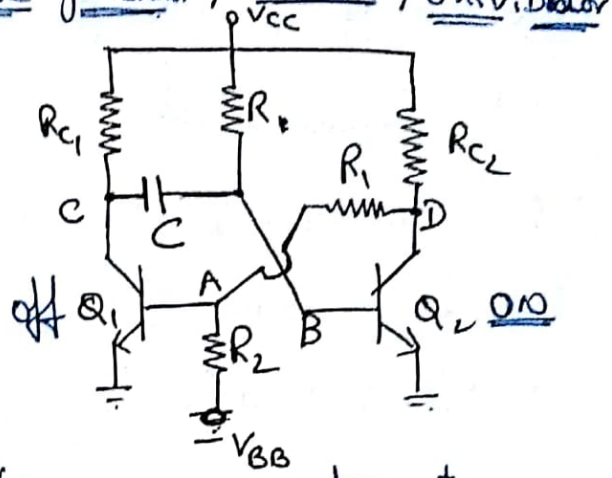
V_{Hy} = Hysteresis voltage

= UTP − LTP

$= V_1 - V_2$



Monostable Multivibrator / Pulse generator / one shot / univibrator

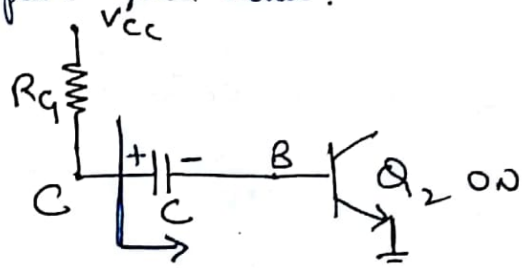


A monostable which has only one stable state & other Quasi-stable state.

Principle of operation:-

Q_1 = Q.S.S & Q_2 = S.S

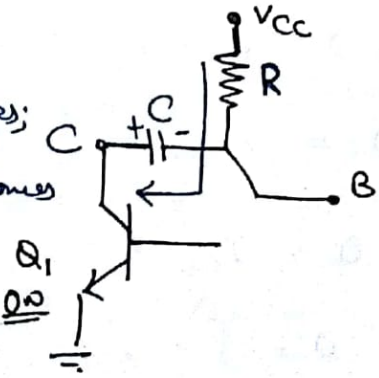
Normally Capacitor is connected to the ON transistor. When Vcc supplied and making $I_2 > I_1$ and making the Q_2 ON & Q_1 off at stable state. then Q_2 is ON then the Capacitor charges by this path given below.



It is obvious that in stable state of the Multivibrator, Q_2 is ON & Q_1 is OFF.

If a negative triggering pulse is applied to the collector of Q_1; it is transmitted to the base of Q_2 through the Capacitor C & makes the base of Q_2 negative & gets Q_2 off the immediately Q_1 gets ON this is only for a shorter duration until the capacitor discharges ⇒ Quasi-stable state.

with Q_1 ON & Q_2 off; the capacitor C finds a discharging path as given below.



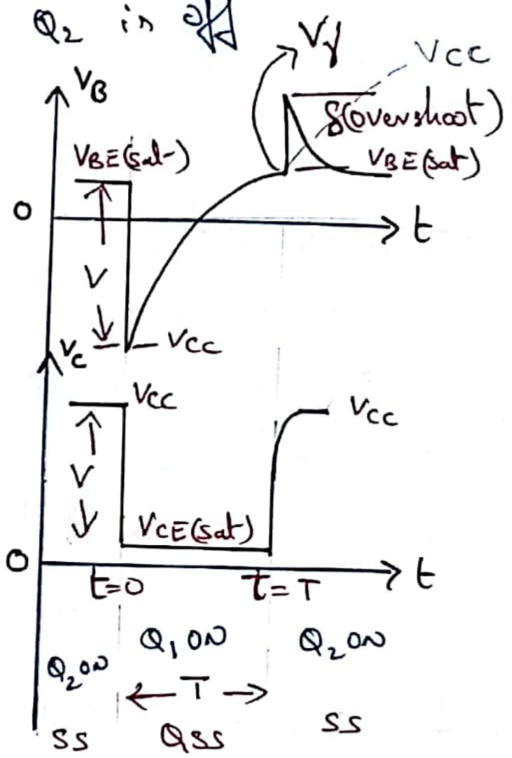
As the capacitor discharges; the potential of pt B becomes less negative,

$V_B = V_\gamma$; of Q_2

As soon as V_B crosses the level of V_γ, Q_2 starts Conducting & gets ON.

In Quasi-stable :- Q_1 ON & Q_2 is off

The duration of the Q.S.S is termed as delay line (or) pulse width (or) gate line. T



As the capacitor discharges the V_B rises exponentially & would attain the value ~~+~~ Vcc at $t = T$ then Q_2 becomes ON & $V_B = V_\gamma$

=) initial value at $t = 0$

=) $V_{B(0)} = V_{in} = -V_{CC}$

=) final value at $t = T$

$$V_{B(T)} = V_{final} = +V_{CC}$$

=) the Voltage ~~dro~~ across the capacitor discharges towards Base of Q_2 V_B is

$$V_B = V_{final} - (V_{final} - V_{initial})\, e^{-t/RC}$$

At $t=T$ =) $V_B = V_\gamma = 0$ (assum ideal value)

$$0 = V_{CC} - (V_{CC} + V_{CC})\, e^{-T/RC}$$

$$0 = V_{CC} - 2V_{CC}\, e^{-T/RC}$$

$$0 = 1 - 2e^{-T/RC}$$

$$2e^{-T/RC} = 1$$

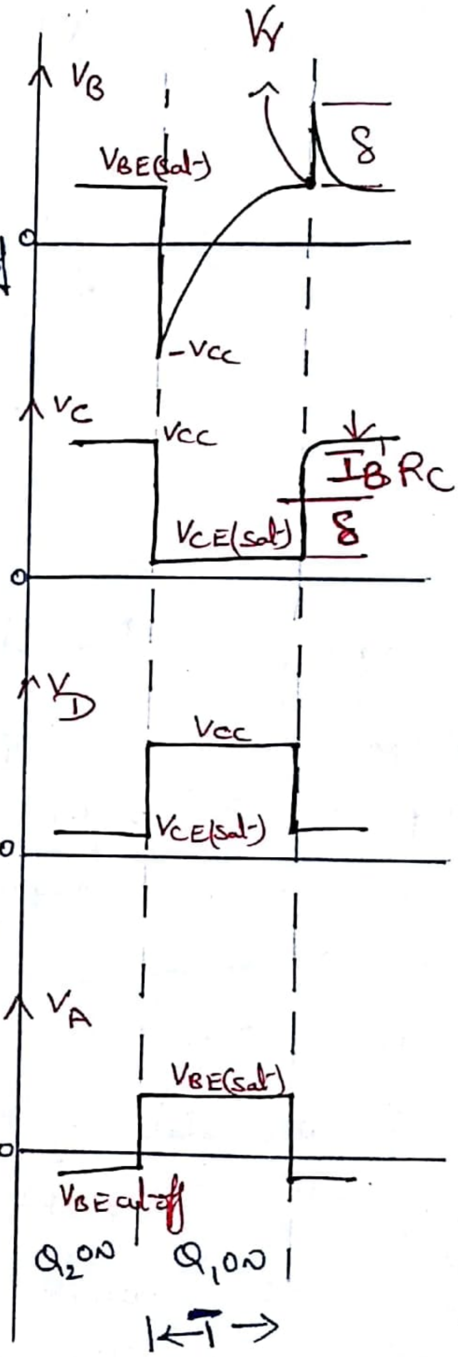
$$\Rightarrow e^{T/RC} = 2 \Rightarrow \frac{T}{RC} = \log_e 2 = 0.69$$

$$\Rightarrow \boxed{T = 0.69\,RC = \text{gate width}}$$

Overshoot "δ" :-

Let $V_B(T-)$ = V_B just prior at end of Q.S.S

$V_B(T+)$ = V_B immediately after end of Q.S.S



$$\Rightarrow V_B(T-) = V_\gamma = [V_{BE(sat)}]$$

$$V_B(T+) = V_{BE(sat)} + I_B' r_{bb'}$$

$r_{bb'}$ ⇒ base spread resistance of Q_2

I_B' = discharge current

At pt B (δ_1)

$$\Rightarrow \delta_1 = V_B(T+) - V_B(T-)$$

$$= V_{BE(sat)} + I_B' r_{bb'} - V_\gamma \quad \text{—(1)}$$

At pt C (δ_2)

$V_C(T-)$ = V_C at prior to the end of Q.S.S

$V_C(T+)$ = V_C Immediately after end of Q.S.S

At ⇒ $t = T$ at pt C

$$V_C(T-) = V_{CE(sat)}$$

$$V_C(T+) = V_{CC} + I_B' R_{C1}$$

$$\delta_2 = V_C(T+) - V_C(T-)$$

$$= V_{CC} + I_B' R_{C_1} - V_{CE(sat)} \longrightarrow (2)$$

Now we consider the overshoot at pt B to equal to the overshoot at pt C

$$\delta = \delta_1 = \delta_2 \qquad (1) = (2) \text{ we get}$$

$$\therefore V_{BE(sat)} + I_B' r_{bb'} - V_\gamma = V_{CC} + I_B' R_{C_1} - V_{CE(sat)}$$

$$I_B'(r_{bb'} + R_{C_1}) = V_{CC} - V_{CE(sat)} + V_\gamma - V_{BE(sat)}$$

$$I_B' = \frac{V_{CC} - V_{BE(sat)} - V_{CE(sat)} + V_\gamma}{r_{bb'} + R_{C_1}}$$

Designing of Monostable Multi

Design a collector - Coupled monostable Multivi to obtain o/p pulses of amplitude 8V, & gating time equal to 20μs, $I_{C(sat)} = 8\,mA$. The base drive required for the on transistor is 1.5 times $i_{B(min)}$. Take the transistor junc voltages as $V_{CE(sat)} = 0.1V$, $V_{BE(sat)} = 0.3V$ $h_{fe(min)} = 20$.

⇒ In stable state of one shot Q_2 on & Q_1 off.

$$V_D = V_{CE(sat)} = 0.1V$$

$$V_B = V_{BE(sat)} = 0.3V$$

$$\Rightarrow i_B = 1.5\, i_{B(min)} \qquad \text{where } i_{B(min)} = \frac{i_{C2}}{h_{fe(min)}}$$

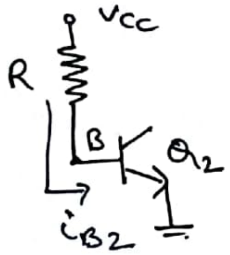
To find R_{C_2}

$$V_D = V_{CC} - i_2 R_{C_2}$$

$$R_{C_2} = \frac{V_{CC} - V_D}{i_2} \qquad i_2 = i_{C_2}$$

To find R

$$\Rightarrow R = \frac{V_{CC} - V_B}{i_{B_2}}$$



$$\Rightarrow i_{B_2} = 1.5\, i_{B_2(min)} \qquad \Rightarrow i_{B_2(min)} = \frac{i_{C_2}}{h_{fe(min)}}$$

To find C

$$\Rightarrow T = 0.69RC$$

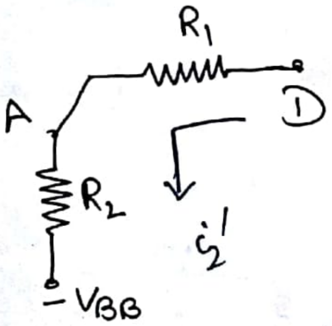
$$C = \frac{T}{0.69R}$$

To find V_{BB}

for n-p-n ger $V_{BE(cut\text{-}off)} = -1.5V$

n-p-n Si $V_{BE(cut\text{-}off)} = -1V$

$$V_A = V_{BE(Q_1)}$$



$$i_2' = \frac{V_D - (-V_{BB})}{R_1 + R_2} = \frac{V_D + V_{BB}}{R_1 + R_2}$$

$$\because R_1 = R_2 \Rightarrow \frac{V_D + V_{BB}}{2R_1} \longrightarrow (1)$$

also we get $i_2' = \dfrac{V_D - V_A}{R_1} \rightarrow (2)$ at A pt.

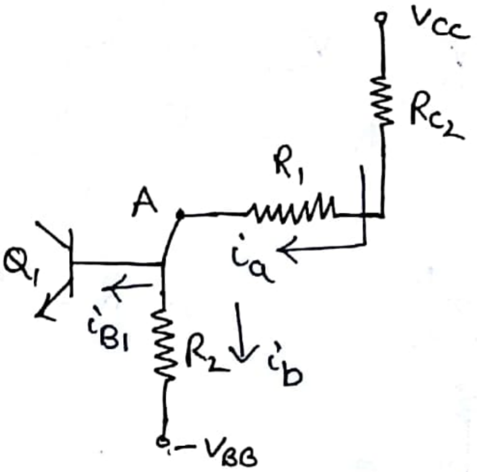
del- (1) = (2) we get

$$\frac{V_D + V_{BB}}{2R_1} = \frac{V_D - V_A}{R_1}$$

$$V_D + V_{BB} = 2(V_D - V_A)$$

$$\underline{V_{BB} = V_D - 2V_A}$$

To find $R_1 = R_2$ ⇒ at Q.S.S when Q_1 ON & Q_2 off.



Let $R_1 = R_2 = R'$

⇒ we known that

$i_{c_2}(\text{cut off}) = 0$

given $i_{B_1} = 1.5\, i_{B_1(min)}$

$$i_a = i_{B_1} + i_b$$

$$i_a = \frac{V_{cc} - V_A}{R_{c_2} + R_1}$$

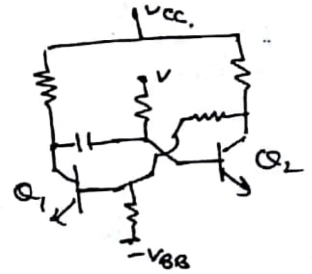
$$i_b = \frac{V_A - (-V_{BB})}{R_2}$$

$$i_a = i_{B_1} + i_b \Rightarrow \frac{V_{cc} - V_A}{R_{c_2} + R'} = 1.5\, i_{B(min)} + \frac{V_A + V_{BB}}{R'}$$

$$\Rightarrow 0.6R'^2 - 3R' + 3.4 = 0$$

$$\Rightarrow R' = \frac{3.7 \pm \sqrt{3.7^2 - 4 \times 0.6 \times 3.4}}{2 \times 0.6}$$

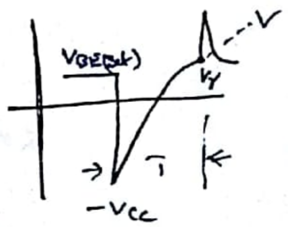
→ max value ⇒ 5.043K as $R_1 = R_2$



Monostable Multi as Voltage to time Converter.

$$\Rightarrow V_B = V_f - (V_f - V_{in})\, e^{-t/RC}$$

$$V_B = V - \{V - (-V_{cc})\}\, e^{-T/RC} \quad \rightarrow V_B = V_\gamma = 0$$



$$0 = V - [V + V_{cc}]\, e^{-T/RC} \Rightarrow (V + V_{cc})\, e^{-T/RC} = V$$

$$\Rightarrow \frac{T}{RC} = \log_e\left(1 + \frac{V_{cc}}{V}\right)$$

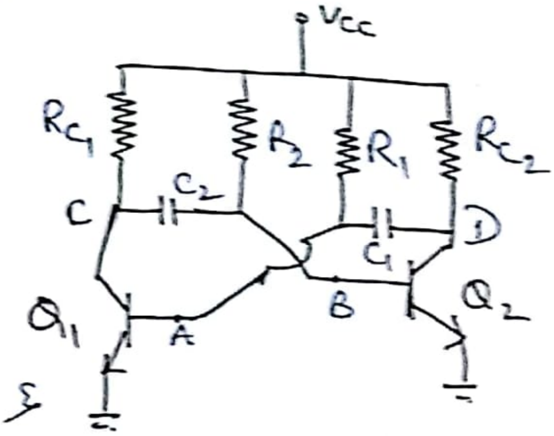
$$\Rightarrow T = RC \log_e\left[1 + \frac{V_{cc}}{V}\right]$$

- Astable Multivibrator / free running Multi / Square wave osc

Astable Multi has two quasi-stable states. & it keeps on switching between these two states by itself.

No external triggering signal is needed.

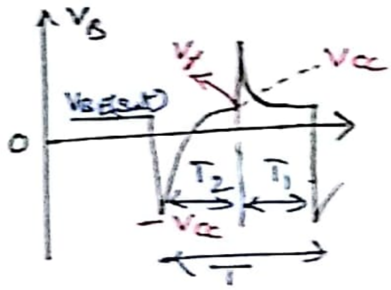
Let assume the Multi is already in action & is osc i.e switching between the 2 states.



Let us assume Q_2 is ON & Q_1 is off

=> Since Q_2 ON then C_2 is charges through R_{C_1} & at same time the C_1 is discharges through R_1. and Q_1 gets off.

=> Expression for T, the period of osc



=> $T = T_1 + T_2$

when the C_2 discharges progressively, the V_B rises exponentially from $-V_{cc}$ upto $V_B = V_\gamma$

, let V_{in} denote the initial value & V_f denote final value of V_B

$$\Rightarrow \quad V_B = V_f - (V_f - V_{in}) e^{-t/R_2C_2}$$

at $V_B = V_\gamma = 0$ & $t = T_2$

$$0 = V_{cc} - [V_{cc} + V_{cc}] e^{-T_2/R_2C_2}$$

$$T_2 = 0.69 R_2 C_2 \quad ---(1)$$

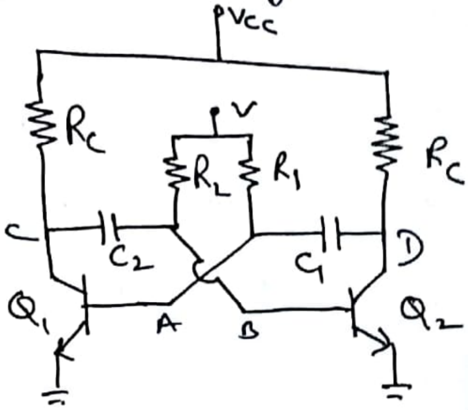
$|||^{ly}$ $$T_1 = 0.69 R_1 C_1 \quad ---(2)$$

Period of Osc $T = T_1 + T_2$ for unsym square wave.

$$T = 0.69\,[R_1C_1 + R_2C_2]$$

if $R_1 = R_2 = R$ & $C_1 = C_2 = C$ for sym. square wave

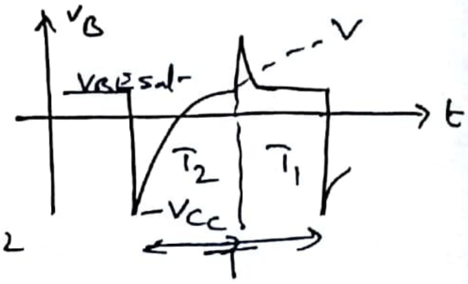
$$T = 1.38\,RC$$



Astable Multi as freq Converter

$V_B = V_{initial} = -V_{cc}$

$V_B = V_{final} = V$



$$\Rightarrow \quad V_B = V_f - (V_f - V_{in})\, e^{-t/R_2C_2}$$

$t = T_2$ & $V_B = V_\gamma = 0$

$$0 = V - (V + V_{cc})\, e^{-T_2/R_2C_2}$$

$$\Rightarrow \quad T_2 = R_2C_2 \log_e\left[1 + \frac{V_{cc}}{V}\right]$$

$$\text{Ily} \quad T_1 = R_1C_1 \log_e\left[1 + \frac{V_{cc}}{V}\right]$$

$$\Rightarrow T = T_1 + T_2$$

$$= (R_1C_1 + R_2C_2)\log_e\left[1 + \frac{V_{cc}}{V}\right]$$

if Sym. Square wave $R_1 = R_2 = R$ & $C_1 = C_2 = C$

$$T = 2RC \log_e\left[1 + \frac{V_{cc}}{V}\right]$$

$$\Rightarrow f = 1/T = \frac{1}{2RC \log_e\left[1 + \frac{V_{cc}}{V}\right]}$$