9. I-V relationships in active region: (Low to medium freq.)

$$i_E = i_c + i_B = (1+\beta)\, i_B$$

$$i_c = \beta . i_B = \alpha . i_E = \left(\frac{\beta}{1+\beta}\right) . i_E$$

$$\alpha = \frac{\beta}{1+\beta}$$

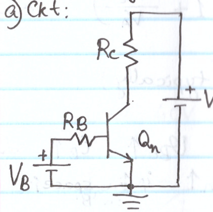
$$\beta = \frac{\alpha}{1-\alpha}$$

npn	pnp
$i_c = I_s . e^{\frac{v_{BE}}{V_T}}$	$i_c = I_s . e^{\frac{v_{EB}}{V_T}}$
$i_E = \frac{i_c}{\alpha} = \frac{I_s . e^{\frac{v_{BE}}{V_T}}}{\alpha}$	$i_E = \frac{i_c}{\alpha} = \frac{I_s . e^{\frac{v_{EB}}{V_T}}}{\alpha}$
$i_B = \frac{i_c}{\beta} = \frac{I_s . e^{\frac{v_{BE}}{V_T}}}{\beta}$	$i_B = \frac{i_c}{\beta} = \frac{I_s . e^{\frac{v_{EB}}{V_T}}}{\beta}$

(without early effect).

10. Active region in common-emitter (CE) configuration:

a) Ckt:

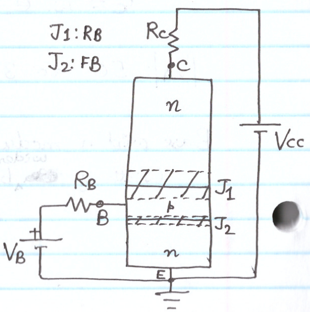


$V_{cc} > V_B$

J_1: RB

J_2: FB

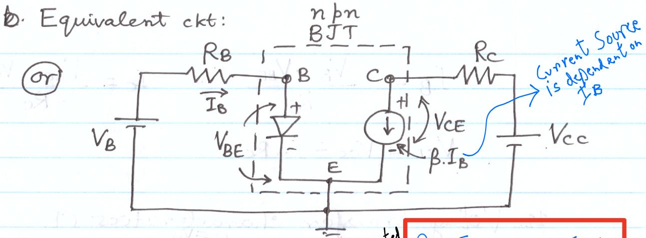
or



$J_1 \Rightarrow$ Reverse biased junction

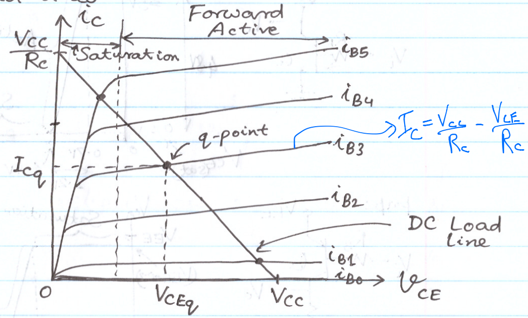
$J_2 \Rightarrow$ Forward biased junction

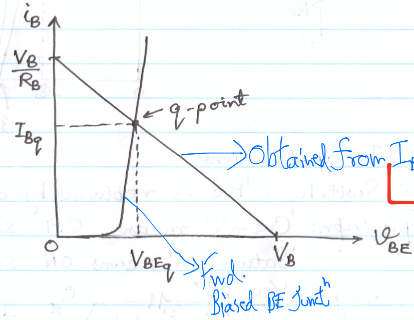
b. Equivalent ckt:



Power Dissipated $\boxed{P_T = I_B V_{BE(on)} + I_C V_{CE}}$

c. Load lines: DC





Obtained from $\boxed{I_B = \frac{V_{BB}}{R_B} - \frac{V_{BE}}{R_B}}$

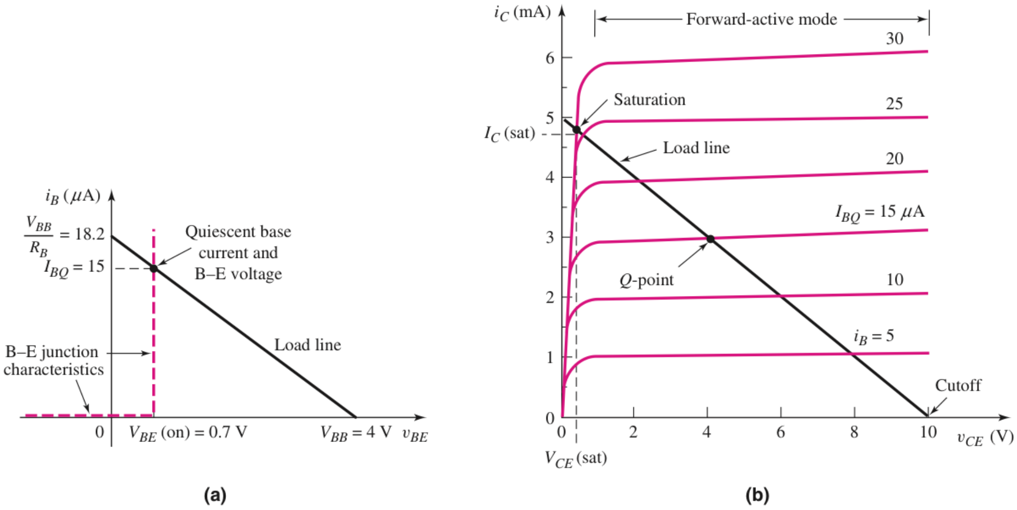


Figure 5.23 (a) Base–emitter junction piecewise linear i–v characteristics and the input load line, and (b) common-emitter transistor characteristics and the collector–emitter load line showing the Q-point for the circuit shown in Example 5.3 (Figure 5.20)

The quiescent point, or Q-point, of the transistor is given by the dc collector current and the collector–emitter voltage. The Q-point is the intersection of the load line and the I_C versus V_{CE} curve corresponding to the appropriate base current. The Q-point also represents the simultaneous solution to two expressions. The load line is useful in visualizing the bias point of the transistor. In the figure, the Q-point shown is for the transistor in Example 5.3.

As V_{BB} increases ($V_{BB} > V_{BE}(\text{on})$), the base current I_B increases and the Q-point moves up the load line. As I_B continues to increase, a point is reached where the collector current I_C can no longer increase. At this point, the transistor is biased in the **saturation mode;** that is, the transistor is said to be in saturation. The B–C junction becomes forward biased, and the relationship between the collector and base currents is no longer linear. The transistor C–E voltage in saturation, $V_{CE}(\text{sat})$, is less than the B–E cut-in voltage. The forward-biased B–C voltage is always less than the forward-biased B–E voltage, so the C–E voltage in saturation is a small positive value. Typically, $V_{CE}(\text{sat})$ is in the range of 0.1 to 0.3 V.

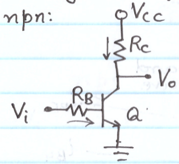
Comment: When a transistor is driven into saturation, we use $V_{CE}(\text{sat})$ as another piecewise linear parameter. In addition, when a transistor is biased in the saturation mode, we have $I_C < \beta I_B$. This condition is very often used to prove that a transistor is indeed biased in the saturation mode.

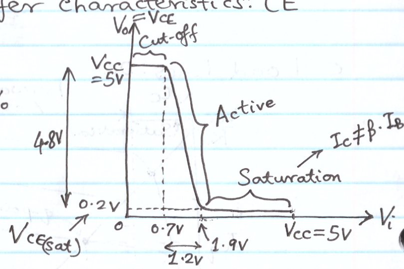
$$I_B = \frac{V_B - V_{BE}}{R_B} \; ; \qquad I_C = \frac{V_{CC} - V_{CE}}{R_C}$$

$$V_{CE} = V_{CC} - I_C \cdot R_C$$

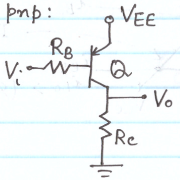
11. Voltage transfer characteristics: CE

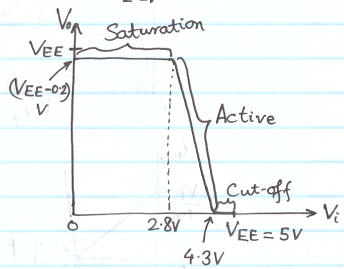
npn:





pnp:





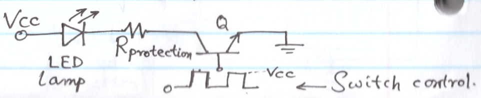
12. BJT applications:

a) Switch : 'Rc' is replaced by a load (e.g. an LED)

pnp/npn: 'Cut-off' means OFF switch 'Q'

'Saturation' means ON switch 'Q'

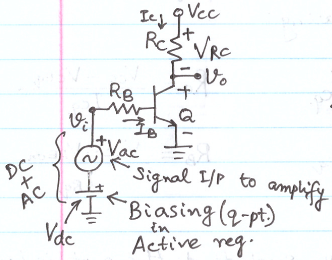
e.g.

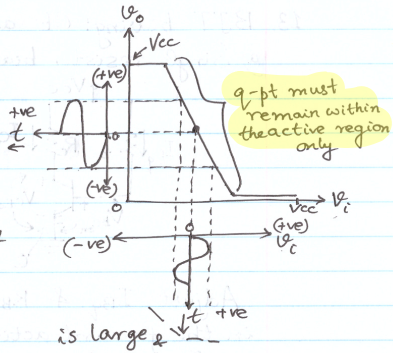


Normalized '0'

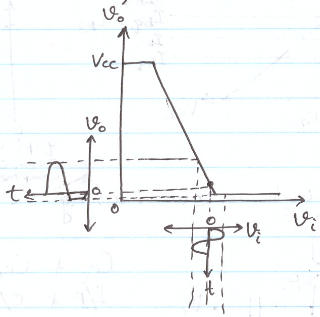
V-amplifier → Low/med. freq

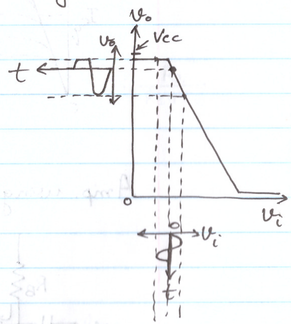
b. Amplifier: CE





For any instance, if v_i is large & forces the transistor Q to operate outside the active region (to either cut-off or saturation), a clipped output voltage (v_o) will appear.





$$\text{Gain (voltage)} : A_V = \frac{\Delta V_o}{\Delta V_i}$$

$$a_v = \frac{\Delta v_o}{\Delta v_i}$$

5.3.1 Switch

Figure 5.44 shows a bipolar circuit called an **inverter,** in which the transistor in the circuit is switched between cutoff and saturation. The load, for example, could be a motor, a light-emitting diode or some other electrical device. If $v_I < V_{BE}(\text{on})$, then $i_B = i_C = 0$ and the transistor is cut off. Since $i_C = 0$, the voltage drop across the load is zero, so the output voltage is $v_O = V_{CC}$. Also, since the currents in the transistor are zero, the power dissipation in the transistor is zero. If the load were a motor, the motor would be off with zero current. Likewise, if the load were a light-emitting diode, the light output would be zero with zero current.

If we let $v_I = V_{CC}$ and if the ratio of R_B to R_C, where R_C is the effective resistance of the load, is less than β, then the transistor is usually driven into saturation, which means that

$$i_B \cong \frac{v_I - V_{BE}(\text{on})}{R_B} \tag{5.34}$$

$$i_C = I_C(\text{sat}) = \frac{V_{CC} - V_{CE}(\text{sat})}{R_C} \tag{5.35}$$

and

$$v_O = V_{CE}(\text{sat}) \tag{5.36}$$

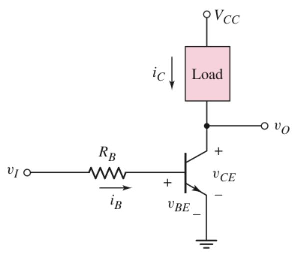


Figure 5.44 An npn bipolar inverter circuit used as a switch

5.3.3 Amplifier

The bipolar inverter circuit can also be used to amplify a time-varying signal. Figure 5.47(a) shows an inverter circuit including a time-varying voltage source Δv_I in the base circuit. The voltage transfer characteristics are shown in Figure 5.47(b). The dc voltage source V_{BB} is used to bias the transistor in the forward-active region. The Q-point is shown on the transfer characteristics.

The voltage source Δv_I introduces a time-varying signal on the input. A change in the input voltage then produces a change in the output voltage. These time-varying input and output signals are shown in Figure 5.47(b). If the magnitude of the slope of the transfer characteristics is greater than unity, then the time-varying output signal will be larger than the time-varying input signal—thus an amplifier.

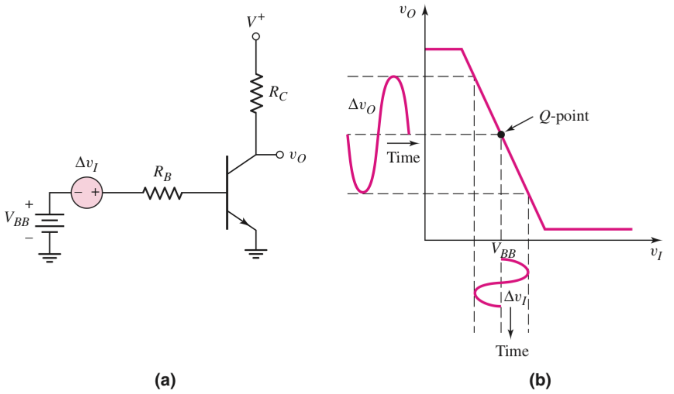
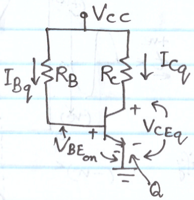


Figure 5.47 (a) A bipolar inverter circuit to be used as a time-varying amplifier; (b) the voltage transfer characteristics

13. BJT biasing: CE as an amplifier (amp.)

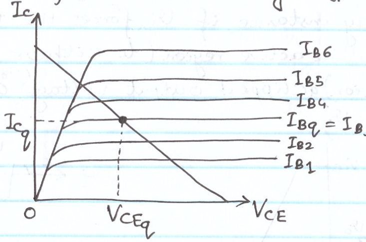
a) Single resistor biasing:

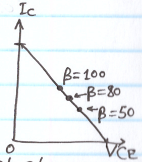


$$R_C = \frac{V_{CC} - V_{CEq}}{I_{cq}}$$

$$R_B = \frac{V_{CC} - V_{BE\,on}}{I_{Bq}}$$

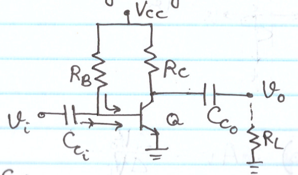
Adjust I_{Bq} & R_B such that the q-pt is located in the forward active region (preferably at the middle)



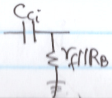


q-pt changes with β even if all other components are same.

Amp. using single resistor biasing



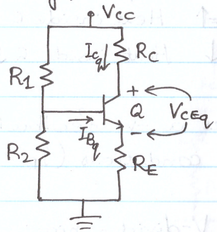
C_{c_i} & C_{c_o} are I/P & O/P coupling capacitors. (eliminates DC offsets at I/P & O/P)



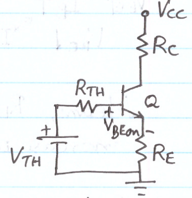
To maintain I_{Bq} when no AC signal is present

Drawback: Bias instability due to temperature change

b) Voltage/resistor divider biasing:



$\approx$



Thevenin's equivalent base driving ckt.

Advantage: Improved bias stability due to temp. change. Ratiometric connection of R_1 & R_2 reduces the change in V_{TH} & R_{TH}, which helps in improving bias stability with temp. variation.

$\because \beta \gg 1$

$$R_{TH} = R_1 // R_2 \approx 0.1(1+\beta) R_E$$

$$V_{TH} = I_{Bq} \cdot R_{TH} + V_{BE_{on}} + I_{Eq} \cdot R_E \approx \frac{R_2}{R_1 + R_2} \cdot V_{CC}$$

$$I_{Eq} = (1+\beta) I_{Bq}$$

$$I_{Bq} = \frac{V_{TH} - V_{BEon}}{R_{TH} + (1+\beta) R_E}$$

$$I_{cq} = \beta \cdot I_{Bq} \approx \frac{V_{TH} - V_{BE\,on}}{R_E}$$

$$V_{CEq} = V_{CC} - I_{cq} R_C - I_{Eq} \cdot R_E$$

Adjust R_1 & R_2 & Vcc such that the q-pt lies at the middle of forward active region.

Purpose of R_E: 1. V-drop additional to V_{BEon} in base ckt.
2. Prevent thermal runaway.

5.4.1 Single Base Resistor Biasing

The circuit shown in Figure 5.51(a) is one of the simplest transistor circuits. There is a single dc power supply, and the quiescent base current is established through the resistor R_B. The **coupling capacitor** C_C acts as an open circuit to dc, isolating the signal source from the dc base current. If the frequency of the input signal is large enough and C_C is large enough, the signal can be coupled through C_C to the base with little attenuation. Typical values of C_C are generally in the range of 1 to 10 μF, although the actual value depends upon the frequency range of interest (see Chapter 7). Figure 5.51(b) is the dc equivalent circuit; the Q-point values are indicated by the additional subscript Q.

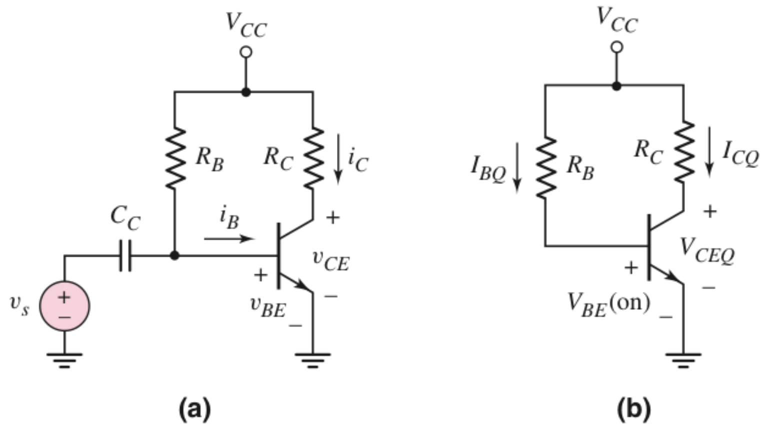


Figure 5.51 (a) Common-emitter circuit with a single bias resistor in the base and (b) dc equivalent circuit

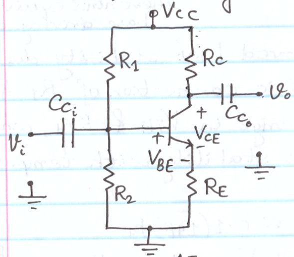
Thermal runaway & its prevention: $-ve\ f/b$

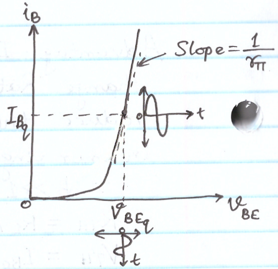
$V_{BE}\uparrow$ $I_B\uparrow$ $I_C\uparrow$ $I_E\uparrow$ Heat inside Q $\uparrow$ $V_{RE}\uparrow$

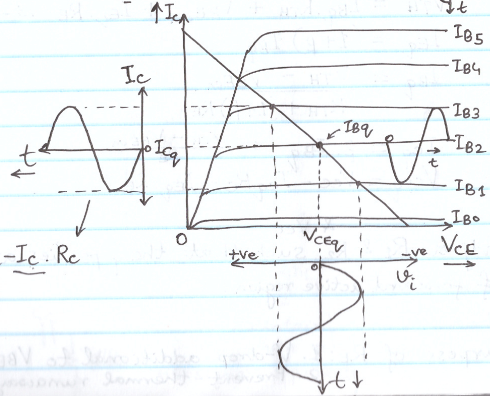
$V_{BE}\downarrow$ $I_B\downarrow$ $I_C\downarrow$ Heat inside Q $\downarrow$

Means, R_E provides a $-ve$ feedback with increase in input conditions (I_B & V_{BE})

Amplifier using V-divider bias:



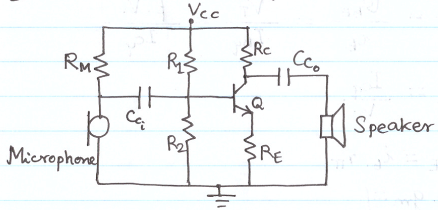




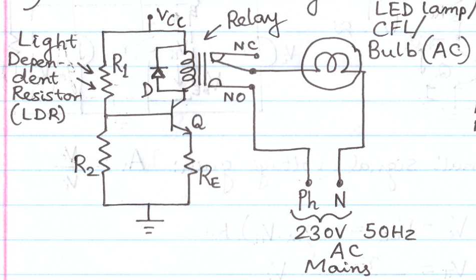
$V_o = V_{CC} - I_C \cdot R_C$

14. Applications of V-divider bias based CE amplifier:

1) Microphone amplifier:



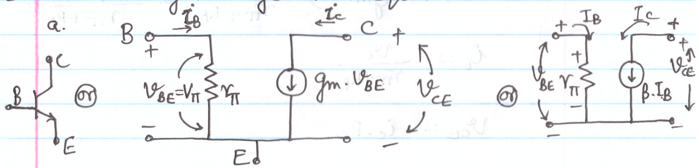
2) Automatic street light controller:



NC : Normally Closed
NO : Normally Open
D : Free-wheeling Diode

15. Small signal hybrid-π equivalent ckt: CE

(Forward active reg.)



r_π = Diffusion res. (B-E I/P res.)

g_m = Transconductance.

$$i_B = \frac{I_s}{\beta} \cdot e^{\frac{v_{BE}}{V_T}} \; ; \quad i_c = I_s \cdot e^{\frac{v_{BE}}{V_T}}$$

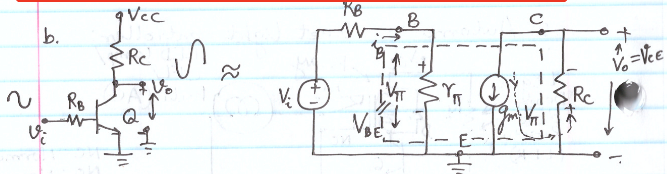
$$r_\pi = \frac{v_{BE}}{i_B} = \frac{V_T}{I_{Bq}} = \frac{\beta \cdot V_T}{I_{cq}}$$

$$g_m = \frac{I_{cq}}{V_T}$$

$$v_{BE} = i_B \cdot r_\pi$$

$$r_\pi \cdot g_m = \beta$$

b.



Small signal voltage gain: $A_v = \frac{V_o}{V_i}$

$$V_o = V_{CE} = -(g_m \cdot V_\pi) \cdot R_C$$

$$V_\pi = \frac{r_\pi}{r_\pi + R_B} \cdot V_i$$

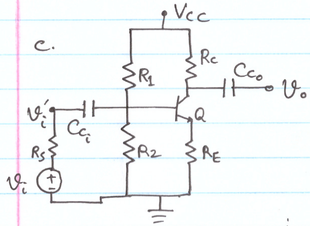
$$\therefore A_v = -(g_m \cdot R_C) \cdot \frac{r_\pi}{r_\pi + R_B} = \frac{-\beta \cdot R_C}{r_\pi + R_B}$$

$$i_B = \frac{v_i}{r_\pi + R_B}$$

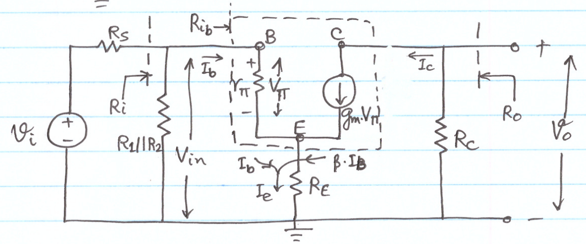
$$v_{CE} = -i_c \cdot R_c$$

Note: Consider '$r_o \| R_c$' if r_o is connected in parallel to '$g_m V_\pi$' I-source.

c.



AC small signal hybrid-π model



$$V_o = -(\beta \cdot I_b) R_C = -I_c \cdot R_c$$

$$V_{in} = I_b \cdot r_\pi + (I_b + \beta \cdot I_b) R_E$$

$$R_{ib} = \frac{V_{in}}{I_b} = r_\pi + (1+\beta) R_E \quad \text{(Resistance Reflection Rule)}$$

$$R_i = R_1 \,//\, R_2 \,//\, R_{ib}$$

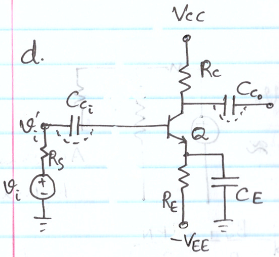
$$V_{in} = \frac{R_i}{R_i + R_s} \cdot V_i$$

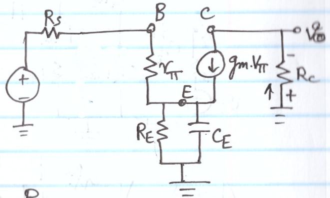
$$A_v = \frac{V_o}{V_i} = \frac{-(\beta \cdot I_b) R_c}{V_i} = -\beta \cdot R_c \cdot \frac{V_{in}}{R_{ib}} \cdot \frac{1}{V_i}$$

$$= \frac{-\beta \cdot R_c}{r_\pi + (1+\beta) R_E} \left(\frac{R_i}{R_i + R_s} \right)$$

$$\cong \frac{-\beta \cdot R_c}{(1+\beta) R_E} \approx -\frac{R_c}{R_E} \quad \left[\because \beta >> 1 \;\&\; R_i >> R_s \right]$$

d.



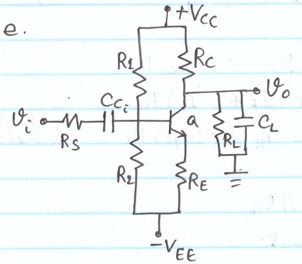


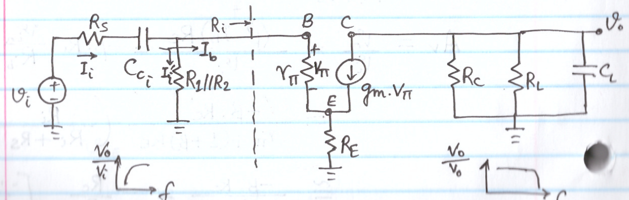
$$|A_v|_{\omega=0} = \frac{g_m \cdot r_\pi \cdot R_C}{R_S + r_\pi + (1+\beta) R_E}$$

C_{c_i} & C_{co} are shorted

$$|A_v|_{\omega=\infty} = \frac{g_m \cdot r_\pi \cdot R_c}{R_s + r_\pi}$$

e.





Lower cut-off

Lower corner freq.: $f_L = \frac{1}{2\pi \tau_s}$ (High Pass Filter)

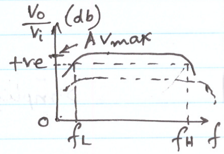
Upper corner freq: $f_H = \frac{1}{2\pi \tau_L}$ (Low Pass Filter)

Upper cut-off

where, $\tau_s = [R_s + (R_1 \| R_2 \| R_i)] \cdot C_c$

& $\tau_L = (R_C \| R_L) C_L$

$R_i = r_\pi + (1+\beta) R_E$



At mid-band:

$$I_i = \frac{v_i}{R_s + (R_1 \| R_2 \| R_i)}$$

$$I_b = \frac{R_1 \| R_2}{(R_1 \| R_2) + R_i} \cdot I_i$$

$V_\pi = I_b \cdot r_\pi$

$v_o = -g_m \cdot V_\pi (R_c \| R_L)$ $\quad C_L \approx$ small

Gain

$$\therefore A_v = -g_m \cdot V_\pi \left[(R_c \| R_L) \cdot \frac{R_1 \| R_2}{(R_1 \| R_2) + R_i} \cdot \frac{1}{R_s + (R_1 \| R_2 \| R_i)}\right]$$

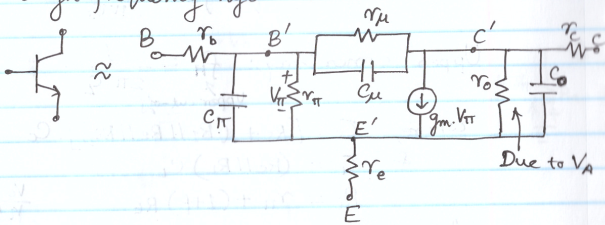
Overall:

Bandwidth: $f_{BW} = f_H - f_L$

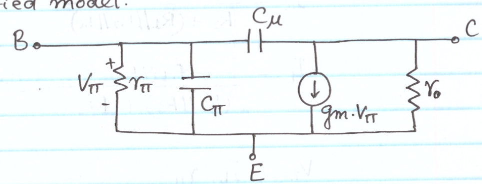
Gain Bandwidth Product: $|A_v|_{max} \cdot f_H \cong$ Constant no./value

r_π, C_π → Provides feedback (-ve)

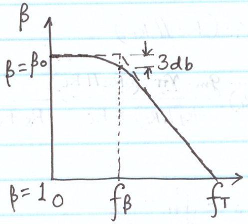
f. High frequency hybrid-π model:

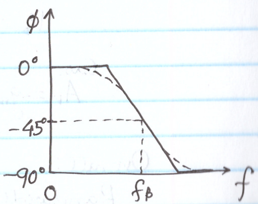


Simplified model:



BJT acts like a LPF (CE)





Bandwidth:

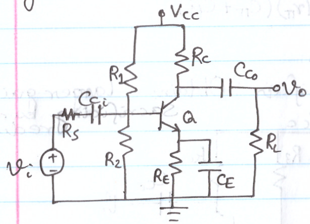
$$f_\beta = \frac{1}{2\pi r_\pi (C_\pi + C_\mu)}$$

Gain Bandwidth Product:

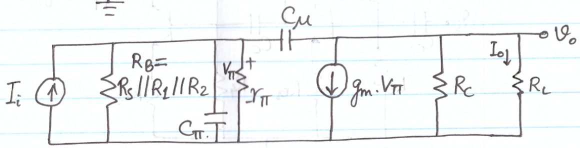
$$f_T = \beta_o \left[\frac{1}{2\pi r_\pi (C_\pi + C_\mu)}\right] = \frac{g_m}{2\pi (C_\pi + C_\mu)}$$

g. Miller effect & Miller Capacitance: High freq.

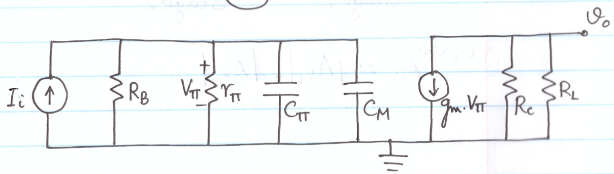
→ Theorem



Convert v_i into a I-source & draw the equ. ckt/model



or



where, $C_M = C_\mu [1 + g_m (R_C \| R_L)] = C_\mu [1 + |A_v|]$

$$v_o = -g_m \cdot V_\pi (R_C \| R_L)$$

$$V_\pi = I_i \left[(R_B \| r_\pi) \| \left(\frac{1}{j\omega C_\pi}\right) \| \left(\frac{1}{j\omega C_M}\right)\right]$$

$$= I_i \frac{R_B \| r_\pi}{1 + j\omega (R_B \| r_\pi)(C_\pi + C_M)}$$

$$A_i = \frac{I_o}{I_i} = -g_m \left(\frac{R_C}{R_C + R_L}\right) \left[\frac{R_B \| r_\pi}{1 + j\omega (R_B \| r_\pi)(C_\pi + C_M)}\right]$$