ECE 340
Lecture 34 : Intro to the BJT - III

Class Outline:

- Normal Mode Operation (Review)
- Current Amplification (Review)
- Common-Emitter Amplifier
- Small-Signal Current Gain

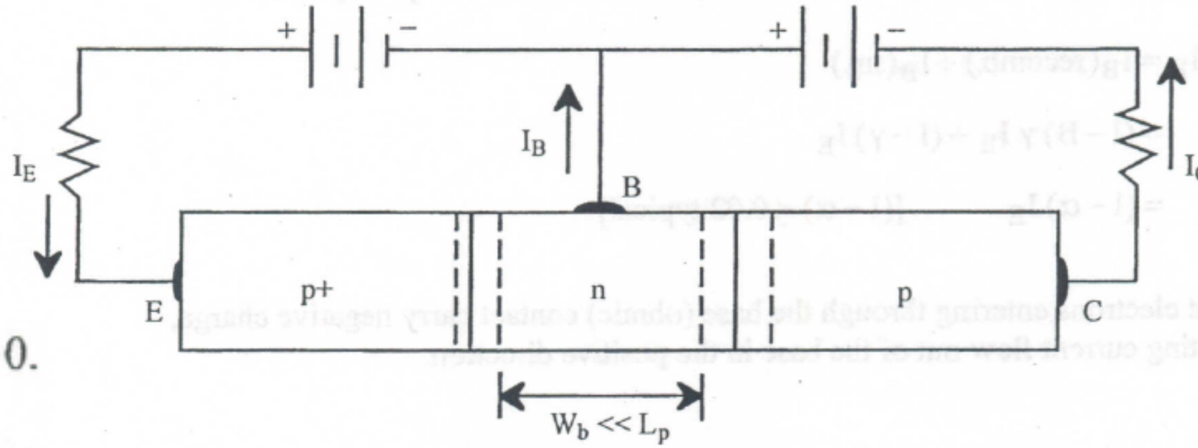
Key Questions

- What is normal operating mode?
- How does a BJT amplify current?
- How do I determine where to set the dc voltages?
- How does the BJT amplify small ac signals?

Normal Mode Operation

The final section of this class has covered the **bipolar junction transistor (BJT)**…

The BJT is shown here in the **common base configuration**.



The emitter current is:

$$I_E = I_B + I_C$$

With corresponding junction biases:

$$V_{EB} > 0.$$

$$V_{CB} < 0$$

So, how does it work?

•Holes are injected as minority carriers across the forward biased emitter p+-n junction into the neutral portion of the n-type base.

•The emitter injection efficiency, γ, is the fraction of the total emitter current due to holes:

$$I_{Ep} = \gamma\, I_E \longrightarrow \gamma = \frac{I_{Ep}}{I_{Ep} + I_{En}}$$

Where this is close to 1 or perfect efficiency.

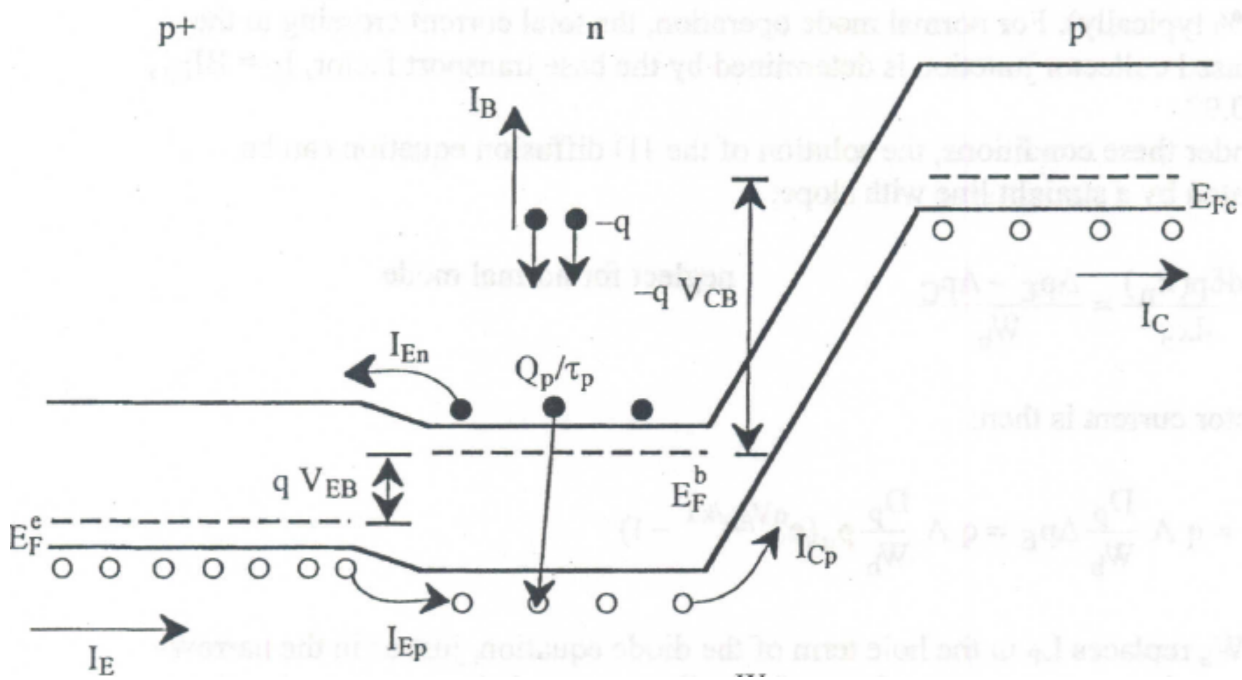
Normal Mode Operation

To understand the various processes at work in a BJT, it helps to utilize a **band diagram**…

•A large fraction of the injected holes diffuses across the narrow base width (W_b << L_p).

•These are then swept into the reverse biased collector junction:

$$I_{Cp} = B\, I_{Ep} = B\gamma\, I_E \quad = \alpha\, I_E$$

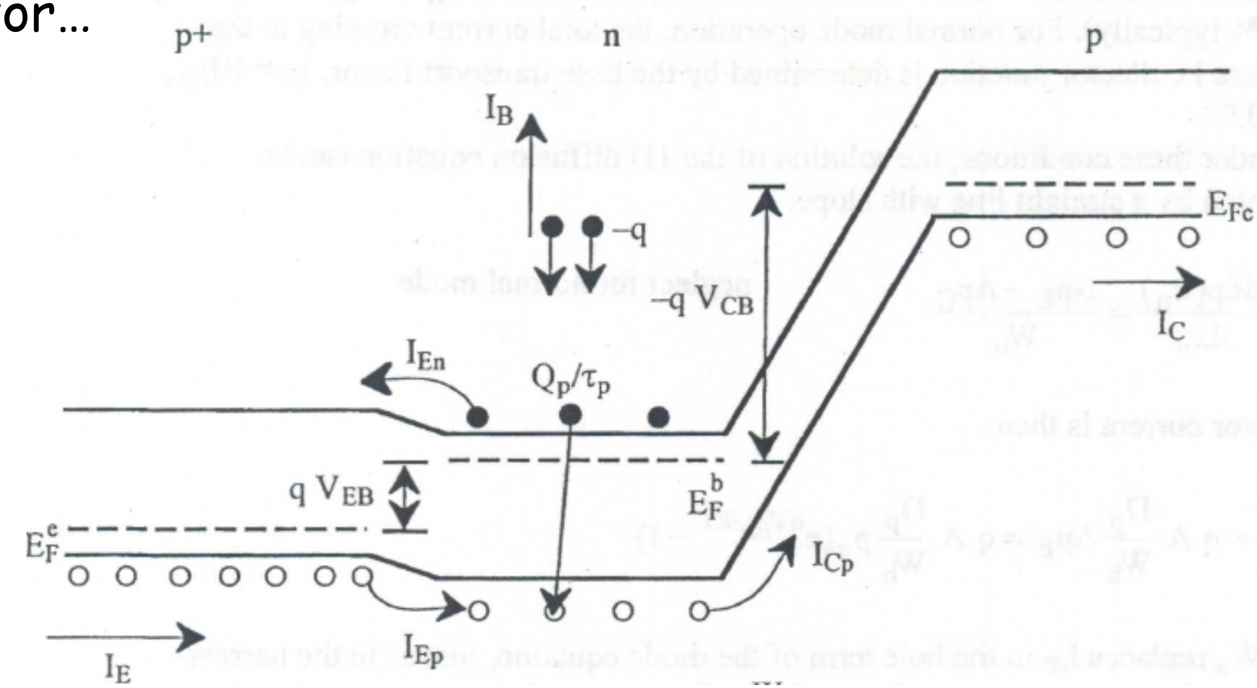


•Here α = Bγ is the current transfer ratio where α is generally very close to unity for a well made transistor.

•Thermally generated electron currents crossing the reverse biased collector junction are negligible in normal mode operation.

Normal Mode Operation

But certainly the base must serve some purpose beyond passing holes from the emitter to the collector…



We need to preserve charge neutrality, so the base must supply electrons.

•This serves two purposes:

- •Replace those which recombine with a small fraction of the holes transiting across the base.
- •Replace those which are injected into the emitter across the CB junction.

$$I_B = I_B(\text{recomb.}) + I_B(\text{inj.})$$

$$I_B = (1-B)\,\gamma\, I_E + (1-\gamma)\, I_E$$

$$I_B = (1-\alpha)\, I_E$$

We should also note that electrons entering through the base contact carry a negative charge which represents current flow out of the base in the positive direction.

Normal Mode Operation

Nevertheless, the most important parameter for a bipolar transistor is the **normal mode current gain**…

$$\beta = \left(\frac{I_C}{I_B}\right)_{\text{normal mode}} = \frac{\alpha}{1-\alpha}$$

- Typical values of β are on the order of 100.
- Please note how each of these parameters are determined by the product of the emitter injection efficiency and the base transport factor.

So what is the **collector current** in our BJT? To answer this we need to know more information about hole diffusion and concentrations.

We can start with the boundary conditions which are set by the different junction voltages:

$$\Delta p_E = p_n(e^{qV_{EB}/kT} - 1) \approx p_n e^{qV_{EB}/kT} \longrightarrow \text{emitter}$$

$$\Delta p_C = p_n(e^{qV_{CB}/kT} - 1) \approx -p_n \longrightarrow \text{collector}$$

Diffusion of minority holes across the base yields a collector current which is given by the gradient in the hole concentration.

$$I_C \approx I_{Cp} = -q\, A\, D_p \left.\frac{dp(x_n)}{dx_n}\right|_{x_n = W_b}$$

Normal Mode Operation

This sound familiar to the narrow-base diode so let's apply the same logic and use the straight line approximation…

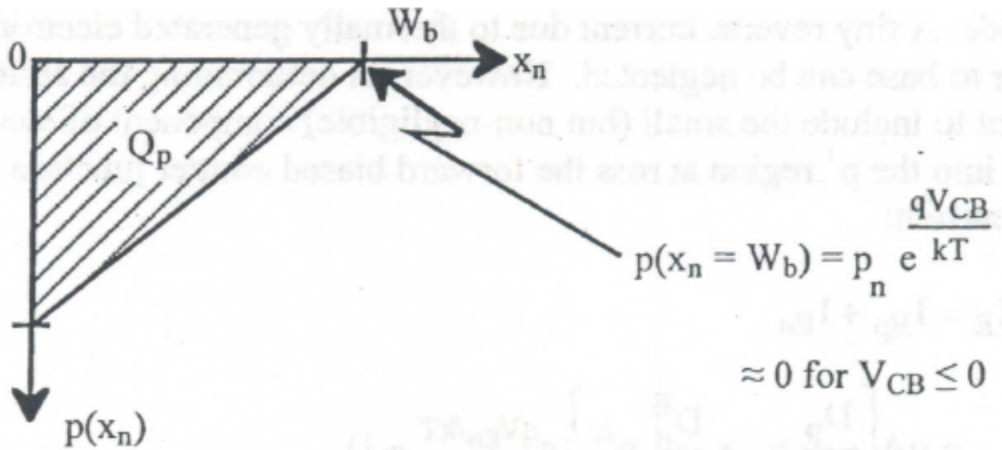
- When the base width, W_b, is narrower than the diffusion length, L_p, the vast majority of holes will make it across the junction to the collector.

- Therefore, minority hole concentration at the beginning of the base must be the same as at the end of the base.

Diffusion equation can be approximated by a straight line with a slope:

$$-\frac{d\delta p(x_n)}{dx_n} \approx \frac{\Delta p_E - \Delta p_C}{W_b}$$

$$p(x_n = 0) = p_n e^{\frac{qV_{EB}}{kT}}$$



Collector current becomes:

$$I_C \approx q A \frac{D_p}{W_b} \Delta p_E = q A \frac{D_p}{W_b} p_n (e^{qV_{EB}/kT} - 1)$$

Note that W_b replaces L_p.

We also ignore the thermally generated current crossing from the collector to the base.

Normal Mode Operation

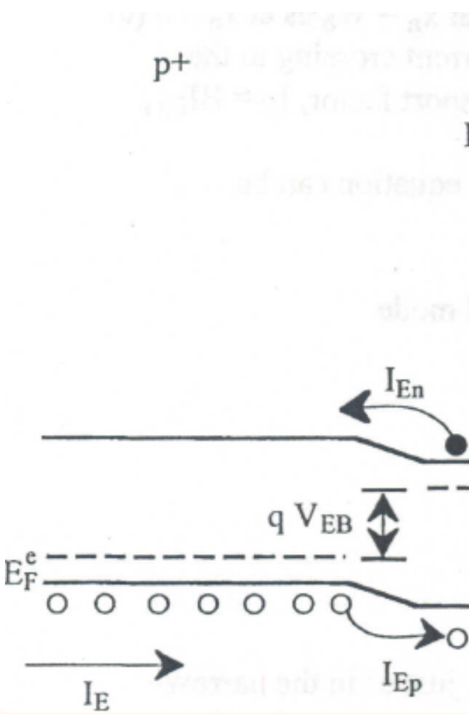
We still need the emitter current…

In doing so, we must include the small component of the electron current injected into the p+ region across the forward biased emitter junction:

$$I_E = I_{Ep} + I_{En} \longrightarrow qA\left[\frac{D_p}{W_b}p_n + \frac{D_n^E}{L_n^E}n_p^E\right]\left(e^{qV_{EB}/kT} - 1\right)$$

Why is the electron current so much smaller than the hole current?

1. The p^+ region is much more heavily doped than the n-type base so $n_p \ll p_n$.
2. A smaller base width, W_b, has replaced the hole diffusion length, L_p, in the denominator of the hole term.

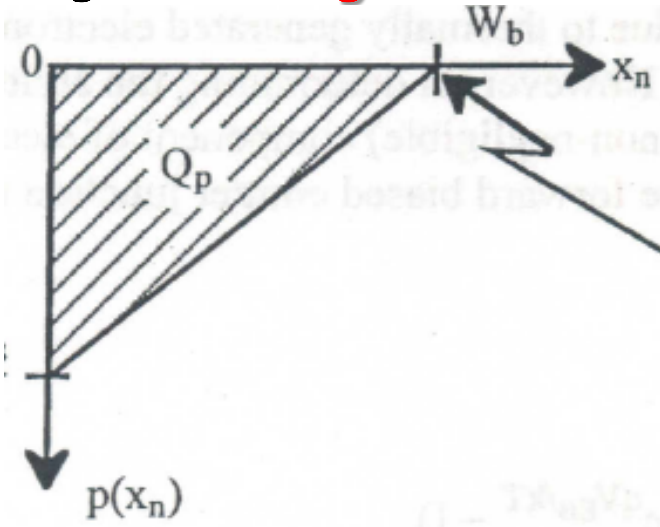


With the emitter and collector current, we can determine the **emitter injection efficiency**:

$$\gamma = \left[1 + \frac{I_{En}}{I_{Ep}}\right]^{-1} \approx \left[1 + \frac{D_n^E}{L_n^E}\frac{W_b}{D_p}\frac{n_p^E}{p_n}\right]^{-1} \longrightarrow \frac{1}{1 + \dfrac{\mu_n^E}{\mu_p^B}\dfrac{W_b}{L_n^E}\dfrac{N_D^B}{N_A^E}}$$

Normal Mode Operation

Like in many things, we can get the base current using the **straight line approximation**…



We need to keep the charge neutral, so the base current must inject electrons to replace those lost.

How much charge is in the base?

$$Q_p = q\,A\,\frac{1}{2}W_b(\Delta p_E + \Delta p_C)$$

So the base current required to offset the electrons lost to recombination with holes is:

$$I_B(\text{recomb.}) = \frac{Q_p}{\tau_p} \longrightarrow \frac{q\,A\,W_b}{2\tau_p}p_n(e^{qV_{EB}/kT}-1)$$

And the base current needed to replace the electrons injected into the p+ emitter:

$$I_B(\text{inj.}) = I_{En} \longrightarrow \frac{q\,A\,D_n^E}{L_n^E}n_p^E(e^{qV_{EB}/kT}-1)$$

$$I_B = I_B(\text{recomb.}) + I_B(\text{inj.})$$

Normal Mode Operation

So what would the BJT operate like if it were ideal?

•Let's quickly examine what would happen if the emitter injection efficiency were ideal…

•Here I_B (Inj.) is much less than I_B (Recomb) and makes a negligible contribution to the base current.

•Based on this, what is the normal mode current gain?

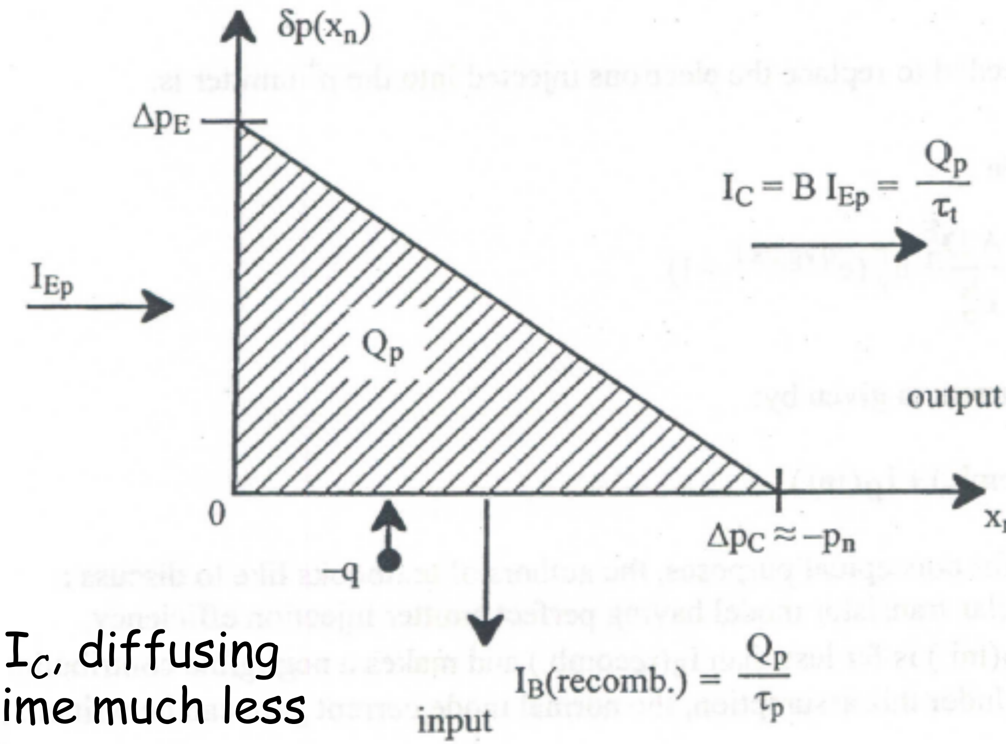
$$\beta \overset{\gamma \to 1}{=} \frac{I_C}{I_B(\text{recomb.})} = \frac{B}{1-B} \xrightarrow{L_P^2 = D_p \tau_p} \frac{\frac{q\,A\,D_p}{W_b}\Delta p_E}{\frac{q\,A\,W_b}{2\tau_p}\Delta p_E} = \frac{2L_p^2}{W_b^2}$$

So for an amplification of 100, we need $W_b \sim L_p/7$ in an ideal case. But what this ideal analysis really gives us is an expression for the **base transport factor**:

$$B \approx 1 - \frac{1}{2}\left(\frac{W_b}{L_p}\right)^2, \quad \text{for } W_b << L_p$$

Current Amplification

Under the proper conditions, we have seen that the ratio between the collector current and the base current, β, can be very large…



- Small ac variations on I_B will be amplified by β on the output current, I_C.
- In a proper circuit, we can vary I_B independently and other junction voltages adjust.
- We can determine the stored charge from I_B.

$$Q_p = I_B(\text{recomb.})\,\tau_p$$

Q_p determines the larger hole current, I_C, diffusing from the emitter to the collector in a time much less than the recombination time… $\tau_t << \tau_p$

$$I_C = \frac{Q_p}{\tau_t}$$

Now assuming unity efficiency, what is the gain?

$$\beta \overset{\gamma\to 1}{=} \frac{I_C}{I_B(\text{recomb.})} = \frac{\tau_p}{\tau_t} >> 1$$

Mean transit time

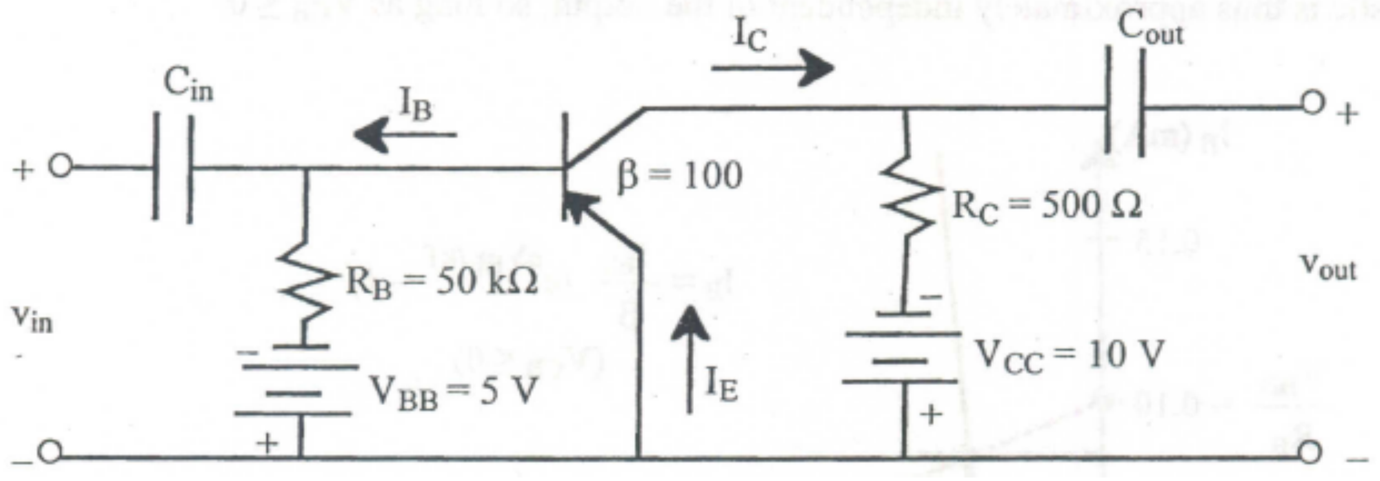
$$\frac{2L_p^2}{W_b^2} \qquad \tau_t = \frac{W_b^2}{2D_p}$$

Common-Emitter Amplifier

Most applications of bipolar transistors involve the use of the **common-emitter amplifier circuit**…

We already know the circuit used for amplification, how is this one different?

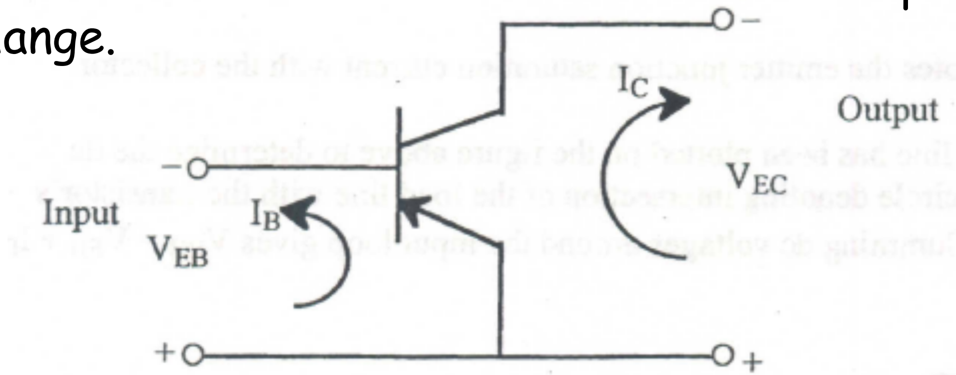
•Coupling capacitors C_{in} and C_{out} have been added.



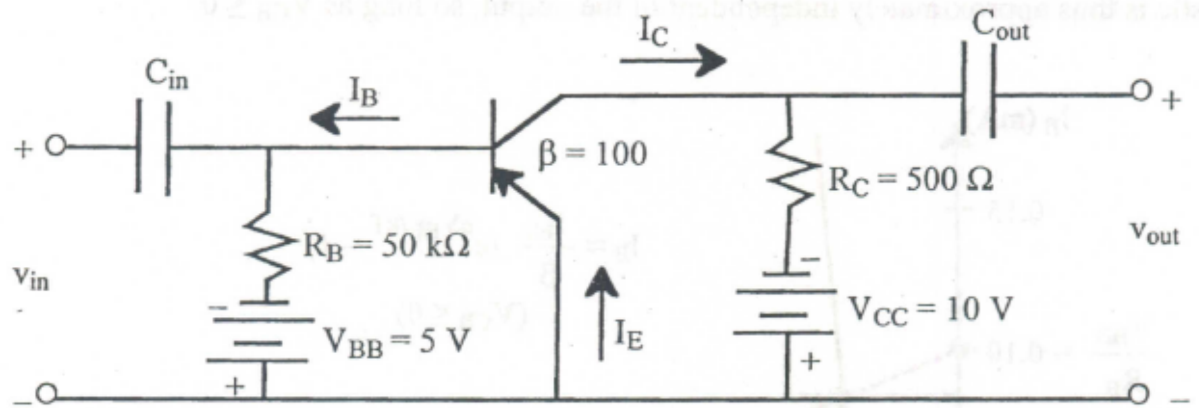
•They work to represent a **short circuit** for ac frequencies 1/iωC compared to other circuit impedances.

•They also represent an **open circuit** to dc current and so the bias conditions set up by the dc sources and resistors will not change.

For a common emitter circuit, input is applied to the base and the output is taken at the collector.



The dc portion of the circuit is designed to put the transistor into normal mode.



Now the collector and base currents are independent of the magnitude of the reverse bias across the collector…

$$I_C = \beta I_B \approx I_{ES}\,(e^{qV_{EB}/kT} - 1) \qquad I_{ES} \approx qA\left(\frac{D_p}{W_b}p_n + \frac{D_n^E}{L_n^E}n_p^E\right)$$

Emitter saturation current

The is independent of the output so long as $V_{CB} < 0$. But what is the dc operating point?

Sum dc voltages around loop:

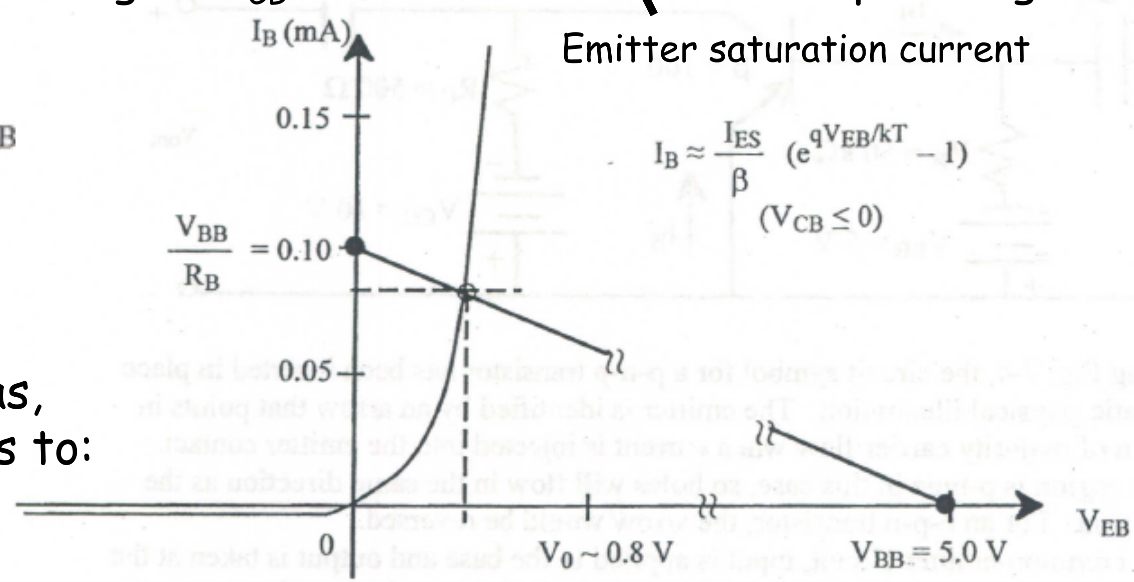
$$V_{BB} = V_{EB} + I_B R_B$$

Then:

$$I_B = \frac{V_{BB} - V_{EB}}{R_B}$$

Because V_{EB} is small in forward bias, the dc operating point corresponds to:

$$I_B \approx \frac{V_{BB}}{R_B} = \frac{5\ V}{50\ k\Omega} = 0.10\ mA$$



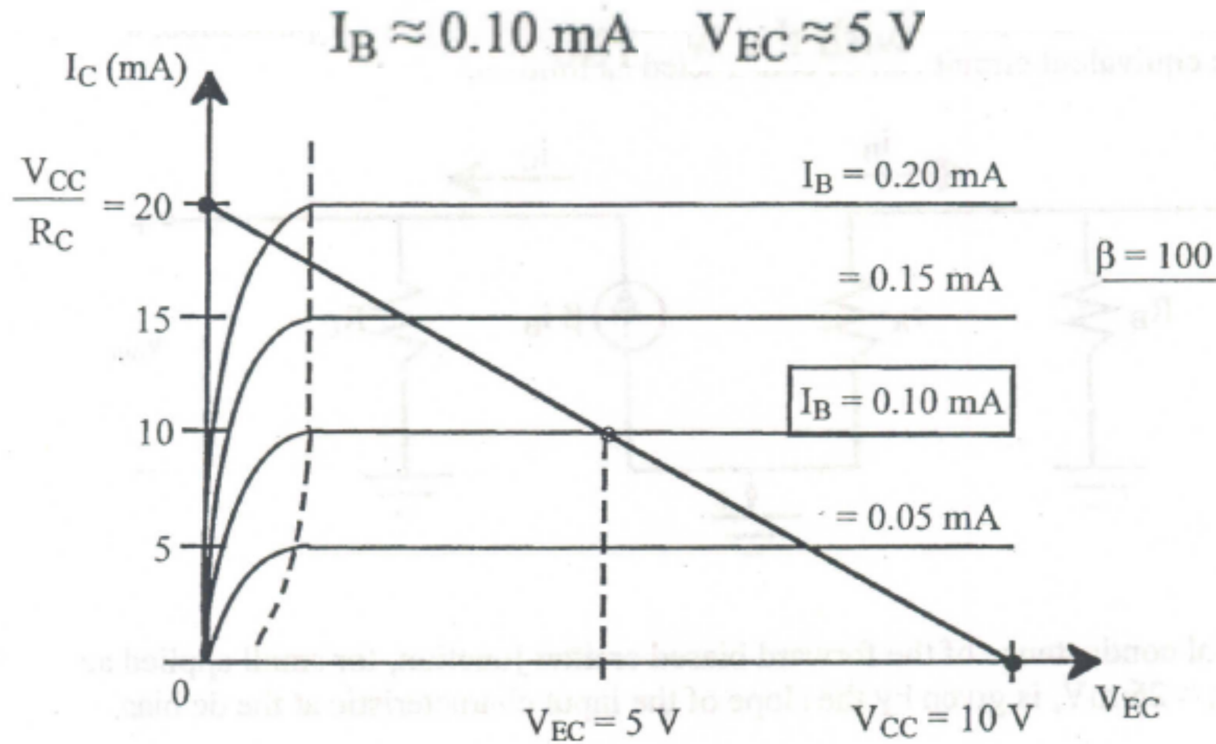
Common-Emitter Amplifier

We can plot the output characteristics for the common-emitter using the base current, I_B, as a parameter.

The voltage across the output can be expressed as the difference between the emitter and the collector junction bias: $V_{EC} = V_{EB} - V_{CB}$

Except close to the origin, the output characteristics are constant: $I_C = \beta I_B$

As $V_{EC} \rightarrow 0$ $V_{CB} \sim V_{EB}$



•Reverse bias on the collector is lost and the output changes and current falls sharply.

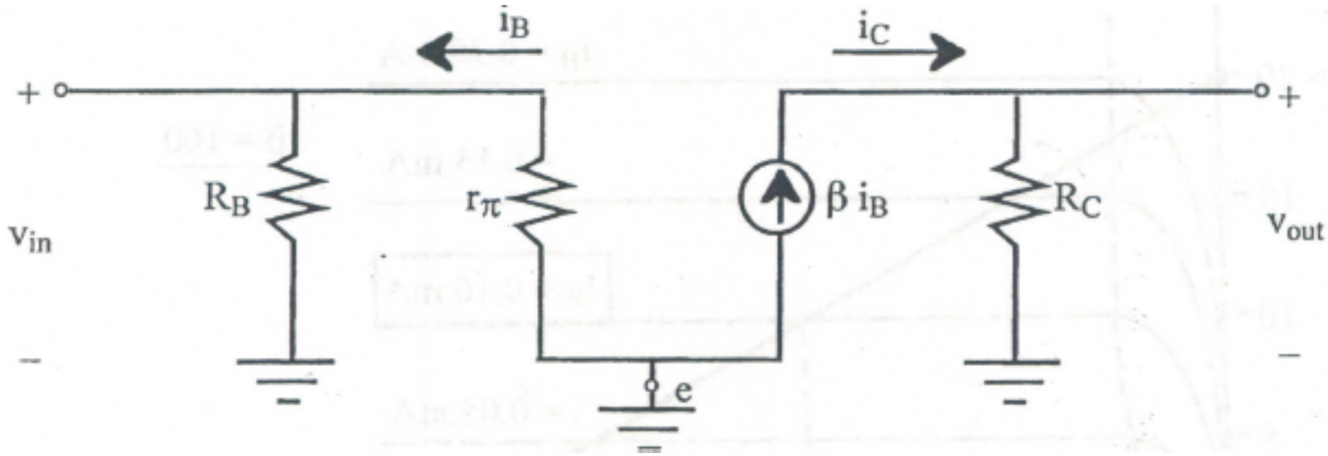
We can obtain the load line by summing voltages: $V_{CC} = V_{EC} + I_C R_C$

$$I_C = \frac{V_{CC} - V_{EC}}{R_C}$$

By placing this point halfway between the ends of the load line ensures the transistor will remain in normal mode over a large bias range.

Small-Signal Current Gain

To characterize the small signal amplification, we can use the simplified ac equivalent circuit shown below…



The differential conductance of the forward biased emitter junction is given by the slope of the input characteristic at the dc bias point:

$$\frac{1}{r_\pi} = \frac{dI_B}{dV_{EB}} \approx \frac{q}{kT} I_B$$

The input voltage, v_{in}, produces a small ac modulation on the base current:

$$i_B = -\frac{v_{in}}{r_\pi}$$

Using our example →

$$r_\pi = \frac{kT/q}{I_B} \approx \frac{0.026\ \text{V}}{0.10\ \text{mA}} \approx 260\ \Omega$$

Small-Signal Current Gain

Good power matching at the input requires $r_\pi \ll R_b$.

By using the load line analysis, our dc component places the circuit in normal operating mode. The induced ac component of the collector current is:

$$i_C = \beta\, i_B = -\beta \frac{v_{in}}{r_\pi}$$

Now evaluate the output voltage under open-circuit conditions with no load resistance:

$$v_{out} = i_C R_C = -\beta \frac{R_C}{r_\pi} v_{in}$$

The open-circuit voltage gain is then given by:

$$\frac{v_{out}}{v_{in}} = -\beta \frac{R_C}{r_\pi}$$

$$\approx -100 \times \frac{500\ \Omega}{260\ \Omega}$$

$$\approx -192$$