UNIVERSITI SAINS MALAYSIA

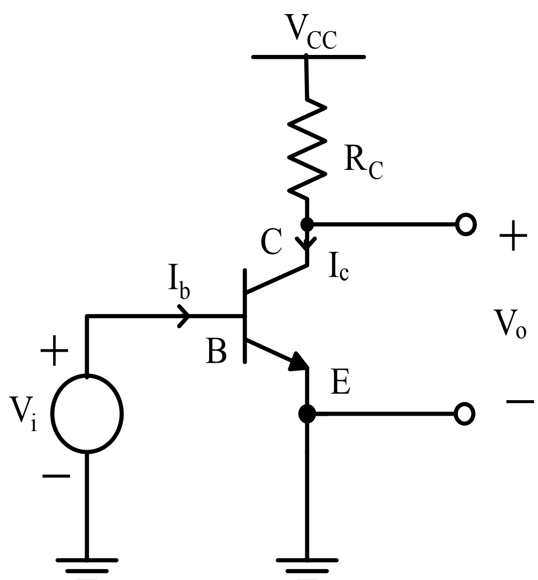
EEE 241
ANALOG ELECTRONICS I
Lectures 2&3 – Single Transistor Amplifiers

DR NORLAILI MOHD NOH

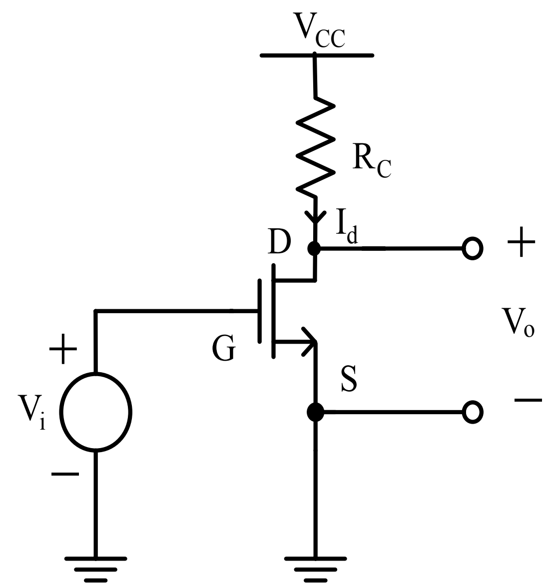
3.3 Basic Single-Transistor Amplifier Stages

3 different configurations :

1. Common-emitter



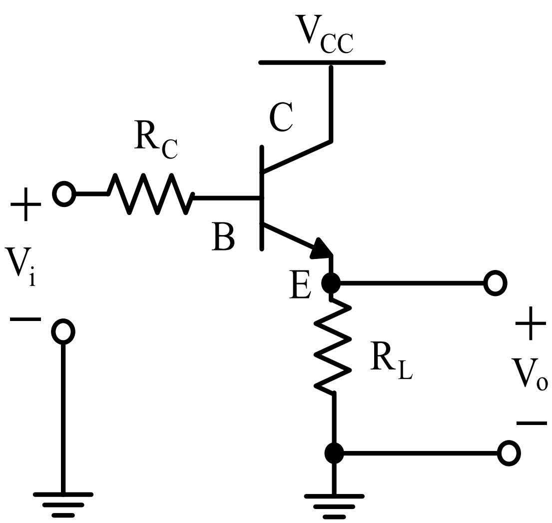
Common-source



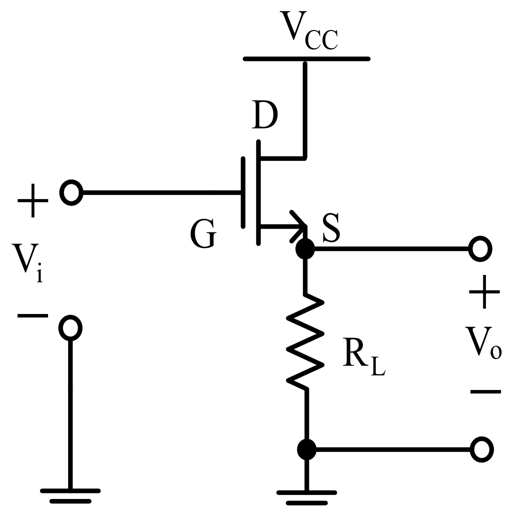
Signal applied to : B G

Amplified output taken from : C D

2. Common-collector (emitter follower)

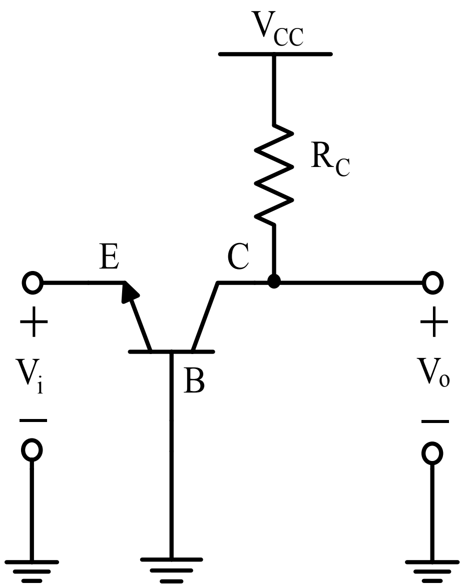


Common-drain (source follower)

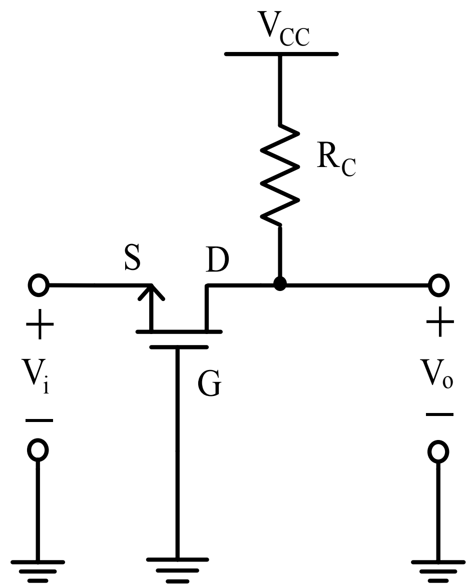


	Common-collector	Common-drain
Signal applied to :	B	G
Amplified output taken from :	E	S

3. Common-base

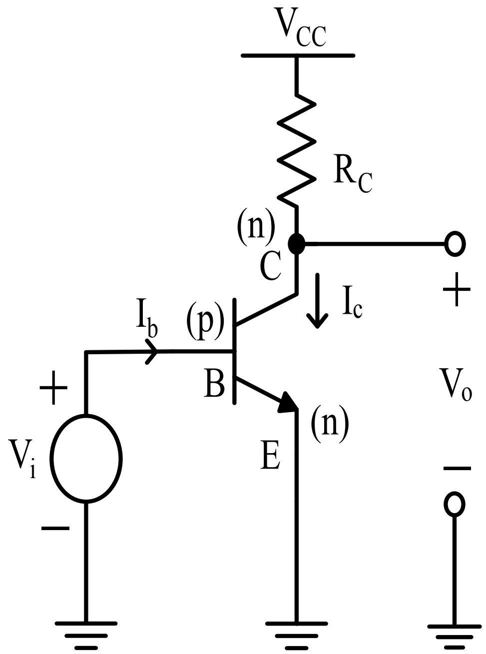


Common-gate



	Common-base	Common-gate
Signal applied to :	E	S
Amplified output taken from :	C	D

Common-emitter configuration



In forward active :

$$I_c = I_s \exp \frac{v_i}{V_T}$$

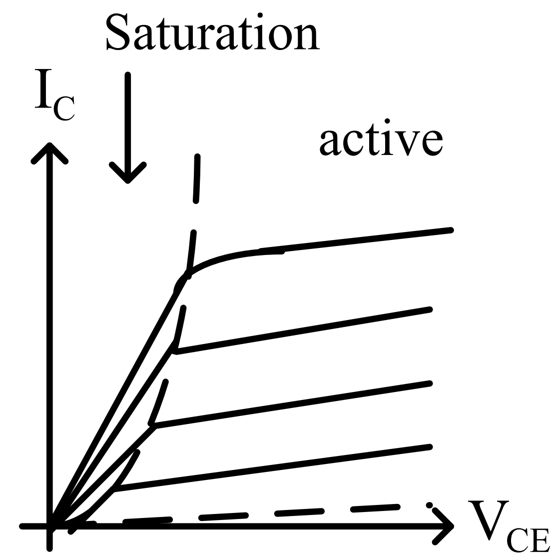
$$I_s = \text{saturated current}$$

$$I_b = \frac{I_c}{\beta_F} = \frac{I_s}{\beta_F} \exp \frac{v_i}{V_T}$$

$$\beta_F = \text{forward current gain}$$

$$V_o = V_{CC} - I_c R_C$$

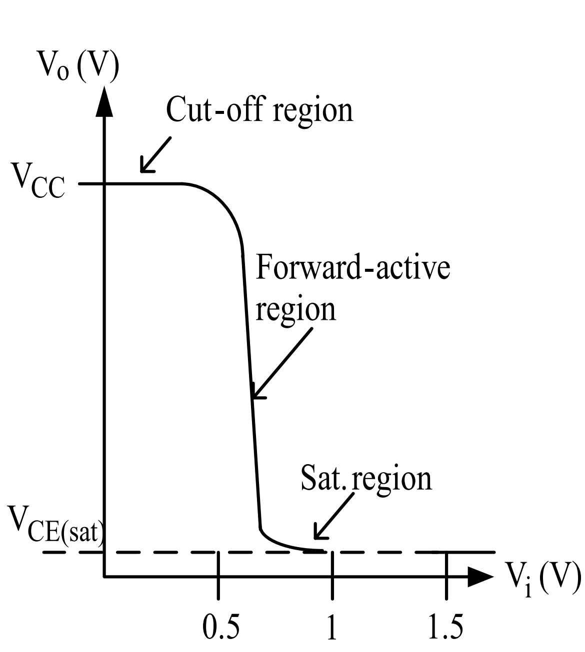
$$= V_{CC} - R_C I_s \exp \frac{V_i}{V_T}$$

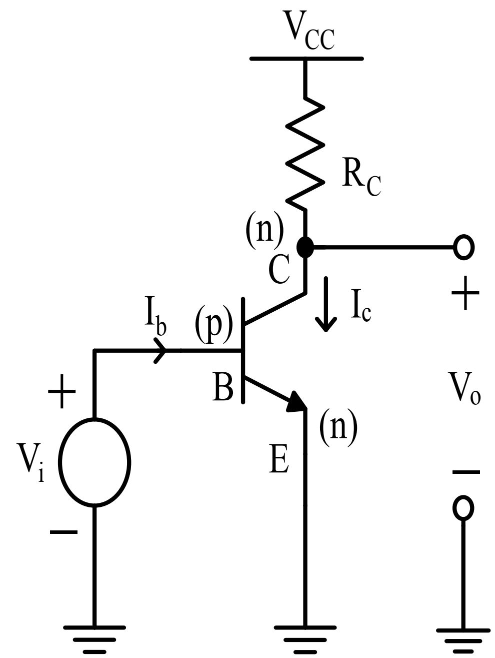


When V_o approaches 0 (i.e. V_{ce} approaches 0), the C-B junction becomes feedback and the device enters saturation. Once the transistor becomes saturated, the output voltage and collector current take on nearly constant values :

$$V_o = V_{CE(sat)}$$

$$I_c = \frac{V_{CC} - V_{CE(sat)}}{R_C}$$





When V_o approaches 0 (i.e. V_{ce} approaches 0), the C-B junction becomes feedback and the device enters saturation. Once the transistor becomes saturated, the output voltage and collector current take on nearly constant values :

$$V_o = V_{CE(sat)}$$

$$I_c = \frac{V_{CC} - V_{CE(sat)}}{R_C}$$

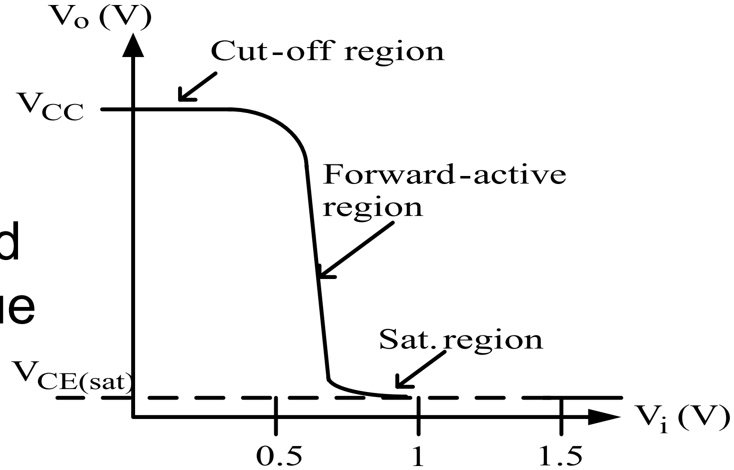
When V_i =0, the transistor operates in the cut off state (as B-E and B-C junctions are both reverse bias) and no current flows other than leakage current I_{CO}.

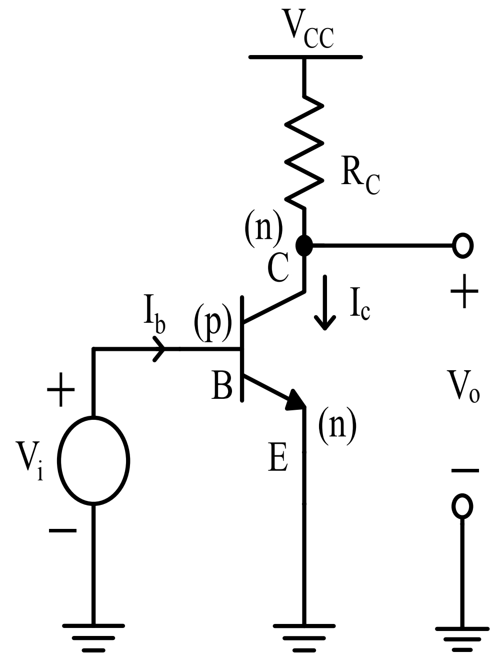
In saturation :

$$V_o = V_{CE(sat)}$$

$$I_c = \frac{V_{CC} - V_{CE(sat)}}{R_C}$$

} fixed value

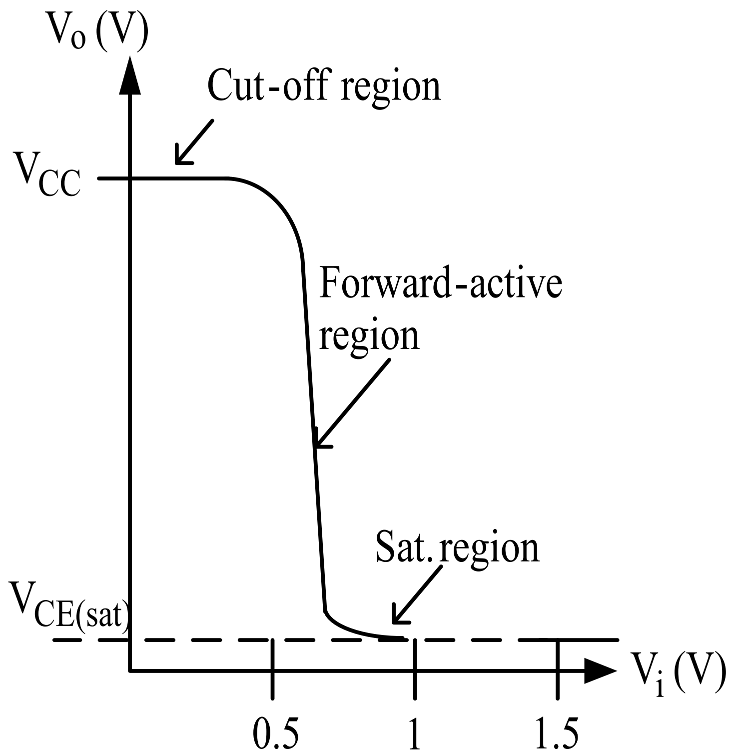




When V_i is high and > V_o , the C-B junction is forward bias. Thus, device is in the saturation region. As V_i is high, I_b is also high. Forward current gain $\beta_F = I_c / I_b$. Forward current gain β_F reduces as transistor leaves the forward-active region of operation and moves into saturation.

In the forward-active region, small changes in the input voltage can give rise to large changes in the output voltage. The circuit thus provides voltage gain.

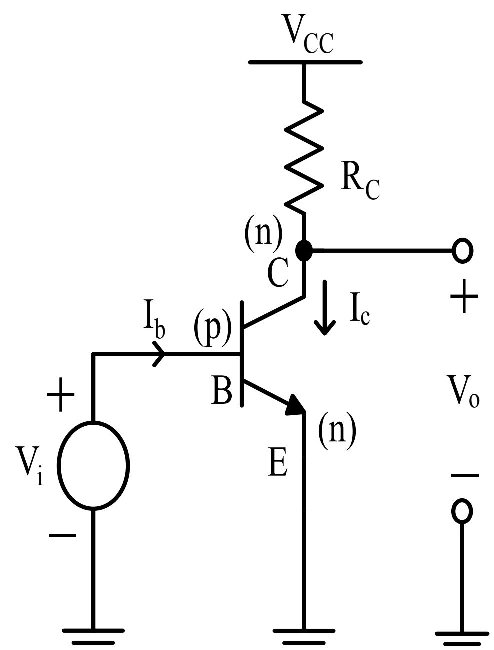
When V_i =0, I_b =0 and I_c =0. $V_{CC} = I_c R_C + V_o$ and since I_c =0, $V_o = V_{CC}$. This is the device operating in the cut off region.



In the forward active region,

$$I_c = I_s \exp \frac{v_i}{V_T}$$

$$I_b = \frac{I_c}{\beta_F}$$

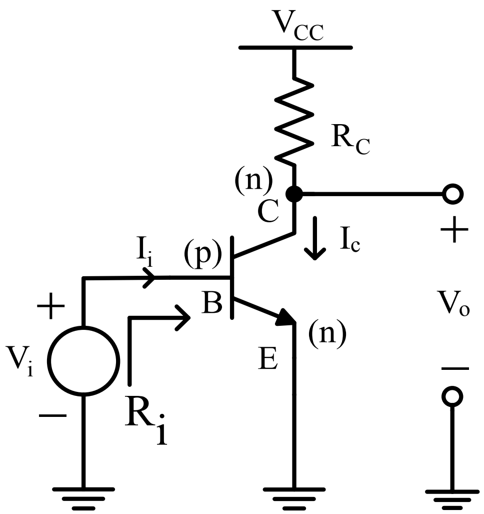


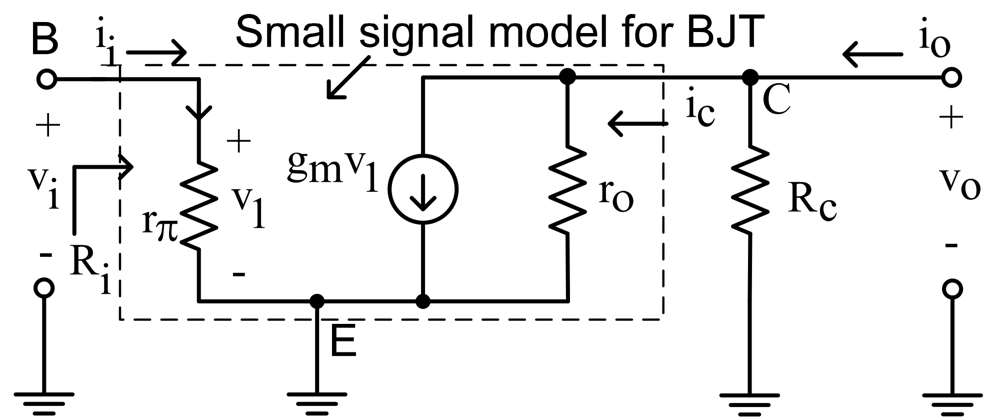
$$V_o = V_{CC} - I_c R_C$$
$$= V_{CC} - R_C I_s \exp \frac{V_i}{V_T}$$

When $V_i \downarrow, I_c \downarrow \therefore V_o \rightarrow V_{CC}$

When $V_i \uparrow, I_c \uparrow \therefore V_o \rightarrow 0$

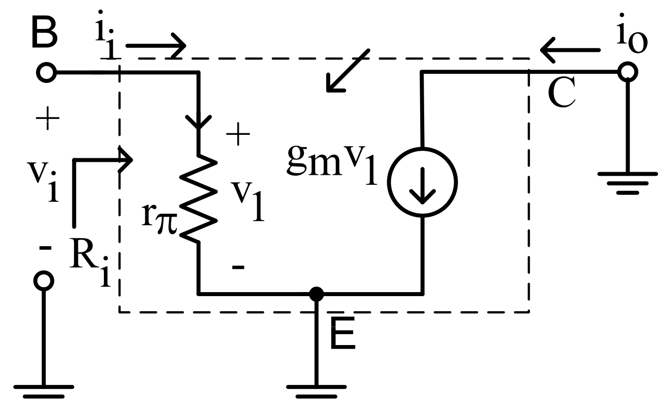
Small-signal circuit of Common-Emitter

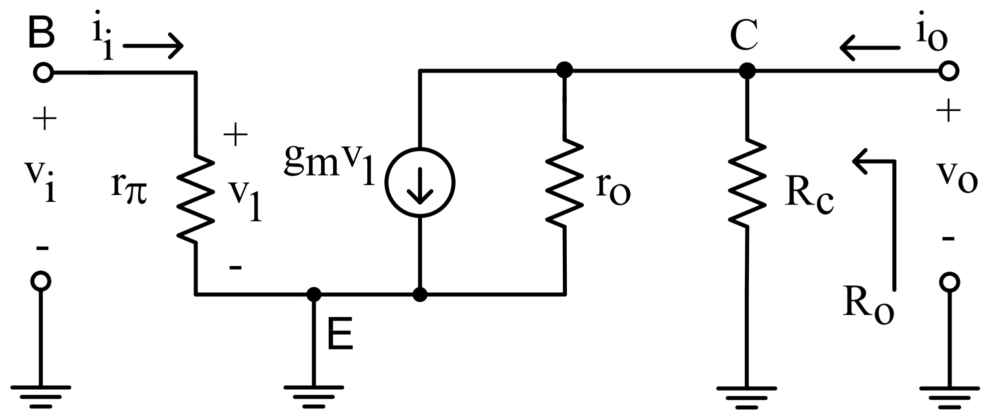


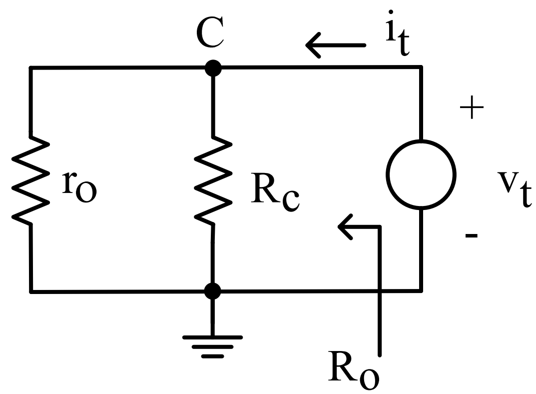


Input resistance $R_i = \frac{v_i}{i_i} = r_\pi = \frac{\beta_o}{g_m}$

Transconductance, $G_m = \left.\frac{i_o}{v_i}\right|_{v_o=0} = \frac{g_m v_1}{v_i} = \frac{g_m v_i}{v_i} = g_m$







Output resistance,

$$R_o = \left. \frac{v_t}{i_t} \right|_{v_i = 0} = r_o // R_C$$

Open-circuit or unloaded voltage gain,

$$a_v = \left.\frac{v_o}{v_i}\right|_{i_o=0} = -\frac{g_m v_1 \, r_o // R_C}{v_i}$$

Since $V_1 = V_i$, then $a_v = -g_m \, r_o // R_C$.

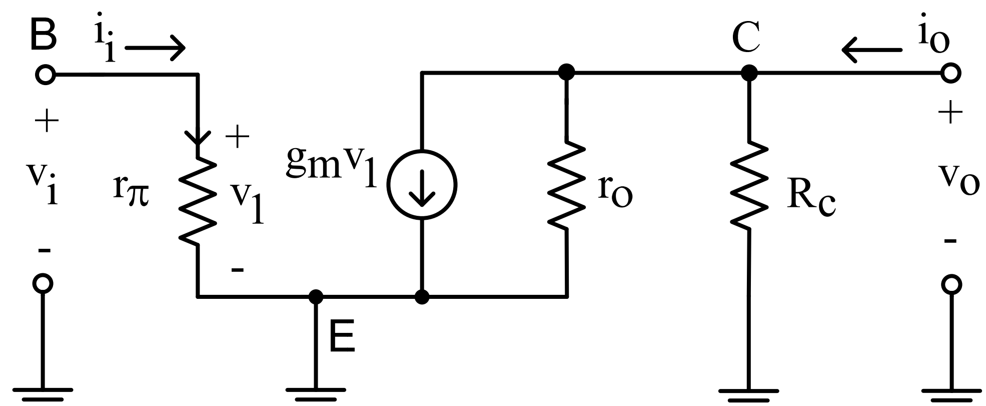
If $R_C \uparrow\uparrow$, then $\lim_{R_C \to \infty} a_v = -g_m r_o = -\frac{I_C}{V_T}\frac{V_A}{I_C} = -\frac{V_A}{V_T} = -\frac{1}{\eta}$

I_c = dc collector current at the operating point

V_T = thermal voltage

V_A = Early voltage

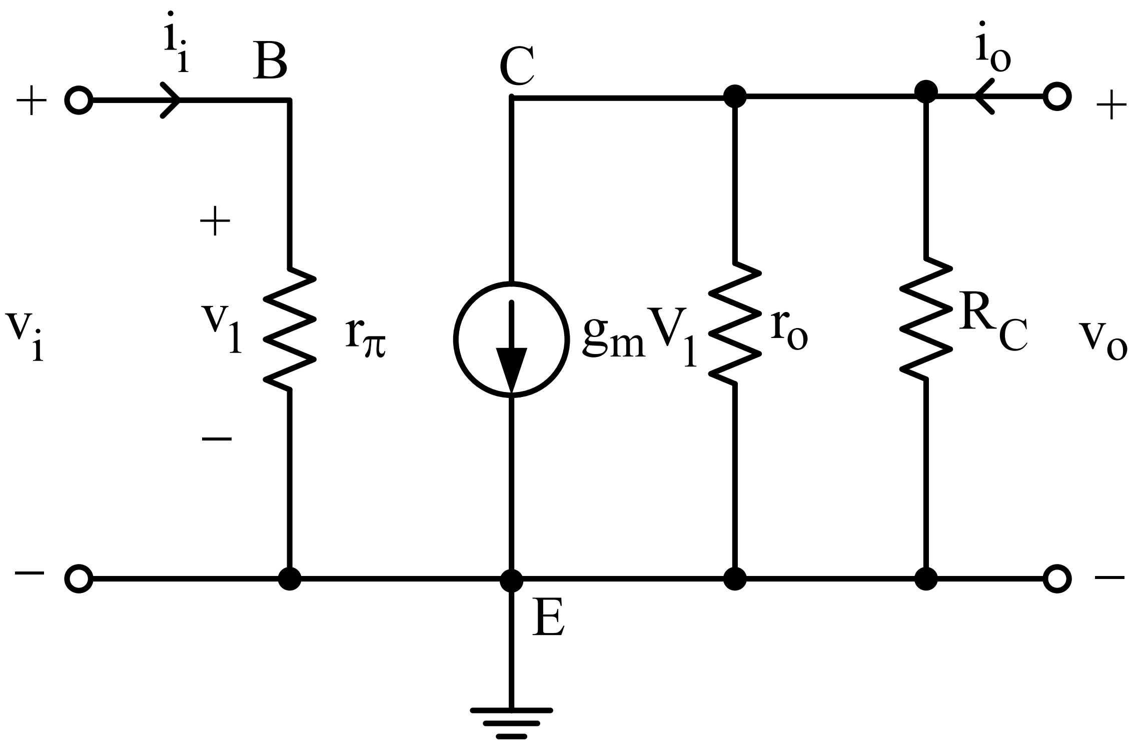
$$\eta = \frac{kT}{qV_A}$$



$$\lim_{R_C \to \infty} a_v = -g_m r_o = -\frac{V_A}{V_T} = -\frac{1}{\eta}$$

represents the max. low-freq. voltage gain obtainable from the transistor. It is independent of the C bias current for BJT and the magnitude is ≈5000 for typical npn devices.

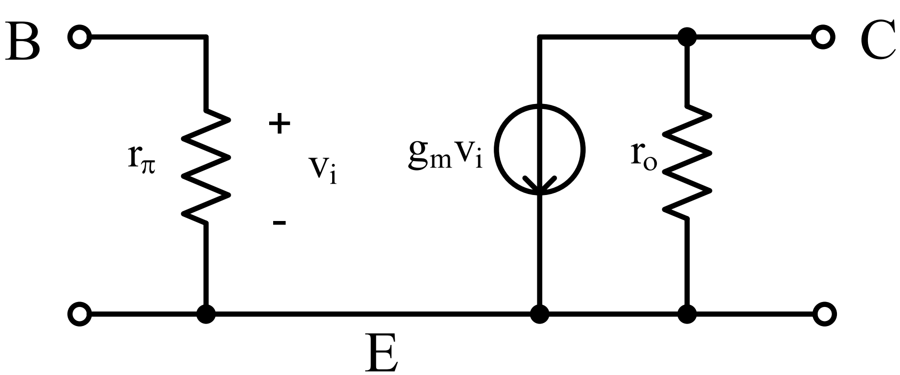
s/c current gain: $a_i = \left.\frac{i_o}{i_i}\right|_{v_o=0} = \frac{g_m v_1}{\frac{v_1}{r_\pi}} = g_m r_\pi = \beta_o$

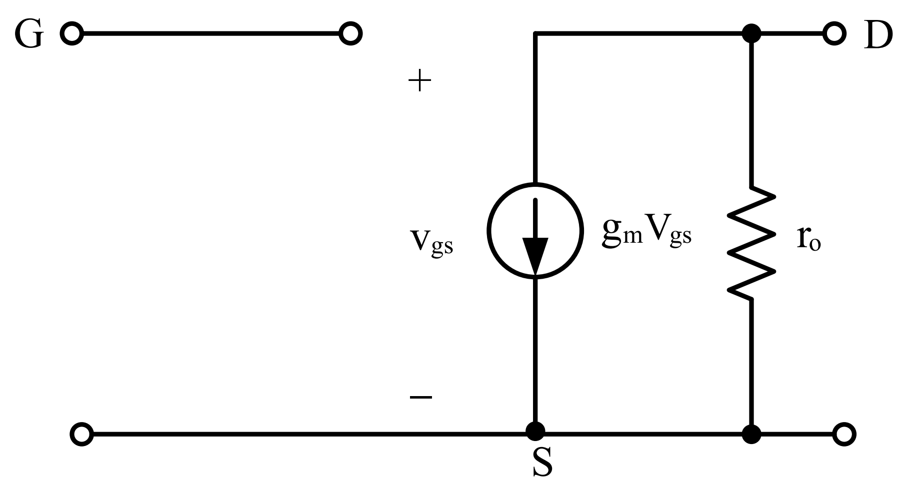


Do example on pg. 178.

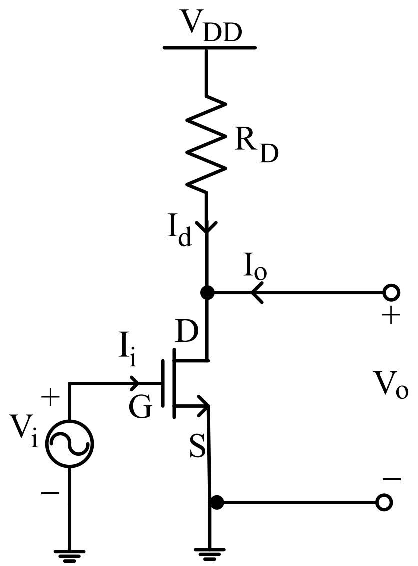
Comparison between the MOS and BJT small signal models :

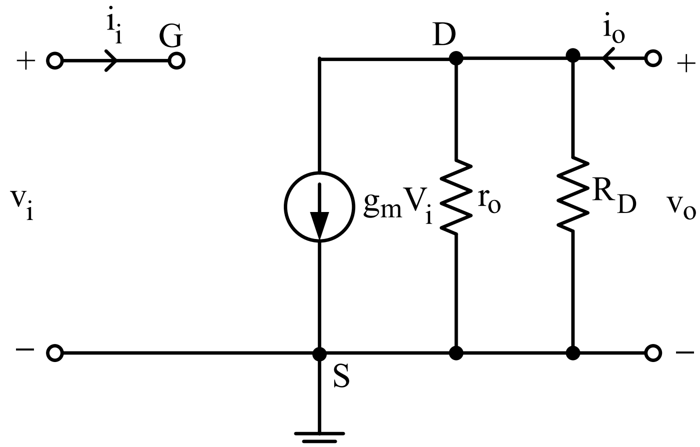
	BJT	MOS
1	r_π input resistance	∞ input resistance from G to S
2	g_m of BJT is higher than that of MOS biased with the same current. Hence, high-gain amplifiers with BJTs are easier to obtain than with MOS.	

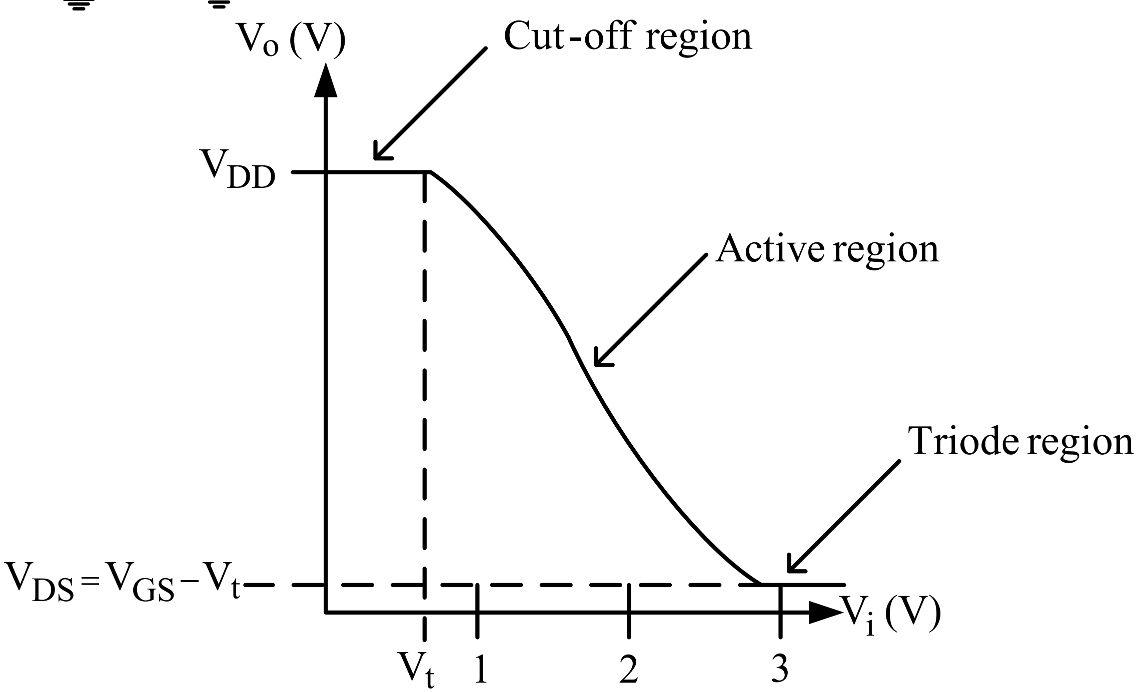




3.3.2 Common-Source (CS) configuration



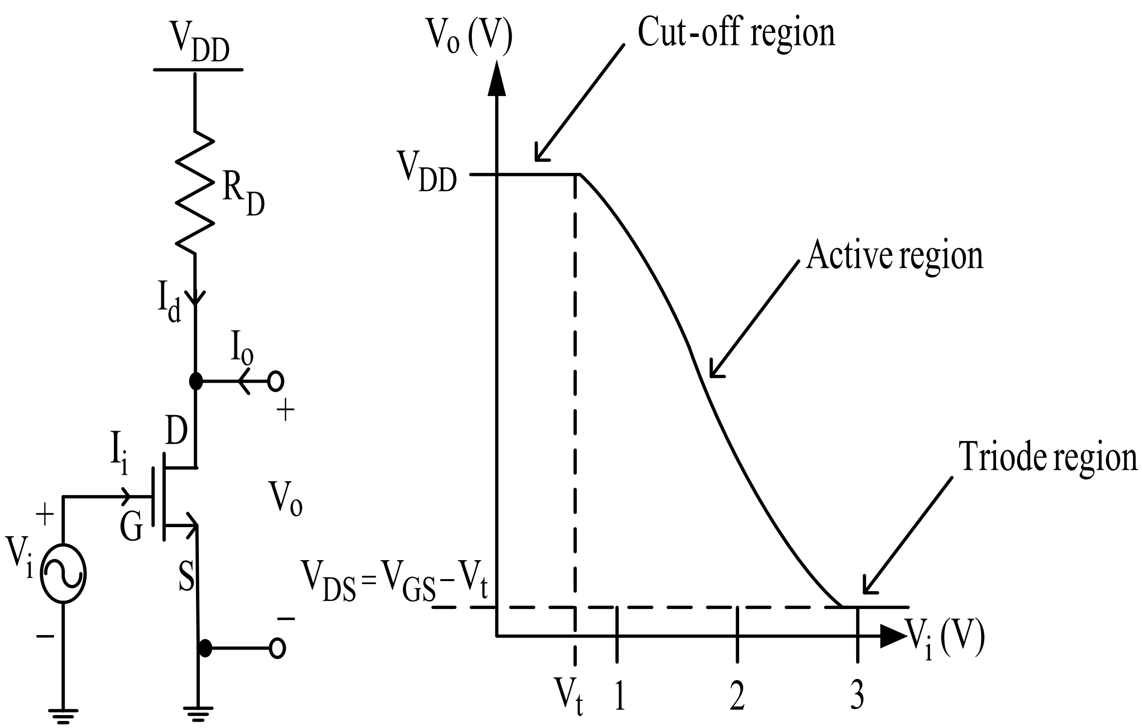




$V_i = 0$, $I_d = 0$

$\rightarrow$cutoff operation

$V_o = V_{DD} - I_d R_d = V_{DD}$



$V_i > V_t$, I_d flows
$\rightarrow$active/sat. operation
$V_o = V_{DS}$ and $V_{DS} > V_{GS} - V_t$
$V_o = V_{DD} - I_d R_D$

For active devices,

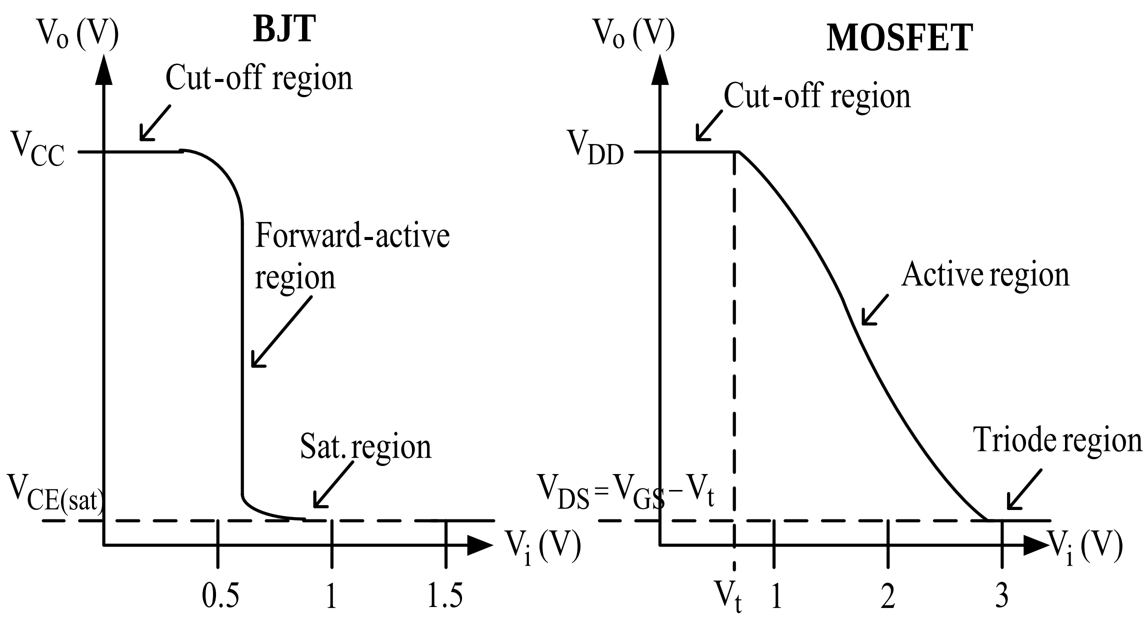
$$I_D = \frac{k'}{2}\frac{W}{L}V_{ov}^2$$

$$V_o = V_{DD} - \frac{k'}{2}\frac{W}{L}V_{ov}^2 R_D$$

$$k' = \mu_n C_{ox}$$

$$V_{ov} = V_{GS} - V_t = V_i - V_t$$

$$V_i \uparrow V_{ov} \uparrow V_o \downarrow$$

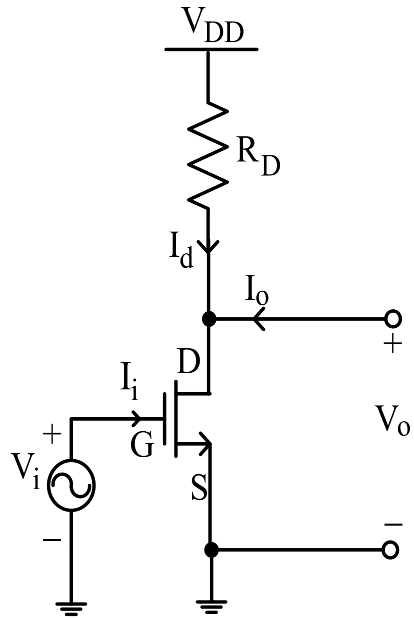


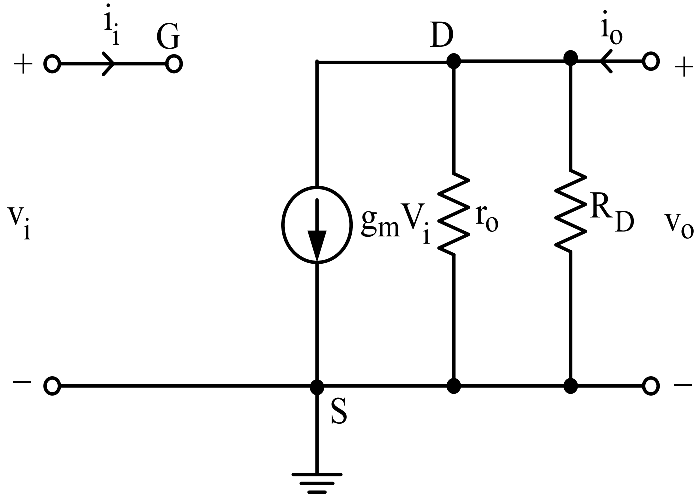
$V_o = V_{DS}$ and $V_{DS} < V_{GS} - V_t$
$\rightarrow$triode operation

$$I_D = \frac{k'}{2}\frac{W}{L}\left[2(V_{GS} - V_t)V_{DS} - V_{DS}^2\right]$$

Output resistance is low and small-signal voltage gain drops dramatically. The slope of this transfer characteristic at any operating point is the small signal voltage gain at that point. As slope for MOS < slope for BJT,

$a_{v(MOS)} < a_{v(BJT)}$



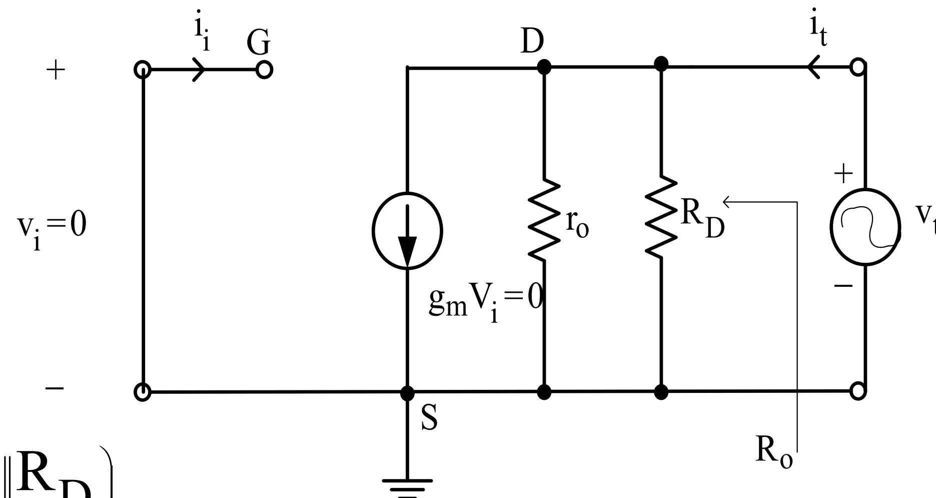


$$G_m = \left.\frac{i_o}{v_i}\right|_{v_o=0} = \frac{g_m v_i}{v_i} = g_m.$$

Hence, transconductance of the circuit, G_m = transconductance of the transistor, g_m

$$R_i = \frac{v_i}{i_i} = \infty$$

$$R_o = \left.\frac{v_t}{i_t}\right|_{v_i=0} = r_o \| R_D$$



o/c or unloaded voltage gain,

$$a_v = \left.\frac{v_o}{v_i}\right|_{i_o=0} = -\frac{g_m v_i (r_o \| R_D)}{v_i} = -g_m (r_o \| R_D)$$

$$a_v = -g_m\left(r_o \| R_D\right)$$

If R_D is very large, $\lim_{R_D \to \infty} a_v = -g_m r_o$ which is the max. possible voltage gain of a one-stage CS amplifier.

$$g_m = \sqrt{2 I_D \mu_n C_{ox} \frac{W}{L}}$$

$$g_m \propto \sqrt{I_D}$$

$$r_o = \frac{1}{\lambda I_D} = \frac{V_A}{I_D}$$

$$r_o \propto \frac{1}{I_D}$$

$$a_v \propto \frac{\sqrt{I_D}}{I_D}$$

$$a_v \propto \frac{1}{\sqrt{I_D}}$$

For BJT, $\lim_{R_C \to \infty} a_v = -g_m r_o = -\frac{V_A}{V_T}$

Therefore, max. voltage gain of MOSFET is dependent on the drain current whereas max. voltage gain of BJT is independent of I_C.

For MOS:

$$g_m = k' \frac{W}{L}(V_{GS} - V_t)$$

$$I_D = \frac{k'}{2}\frac{W}{L}(V_{GS} - V_t)^2$$

$$\frac{g_m}{I_D} = \frac{2}{(V_{GS} - V_t)} = \frac{2}{V_{ov}}$$

$$r_o = \frac{1}{\lambda I_D} = \frac{V_A}{I_D}$$

Hence,

$$\lim_{R_D \to \infty} a_v = -g_m r_o = -g_m \frac{V_A}{I_D} = -\frac{2V_A}{V_{OV}}$$

For BJT:

Hence, $\lim_{R_C \to \infty} a_v = -g_m r_o = -\frac{V_A}{V_T}$

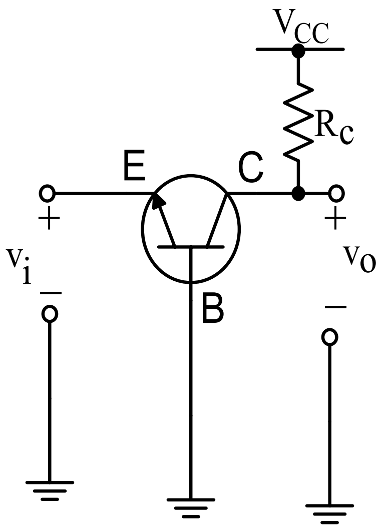
V_T = 26 mV

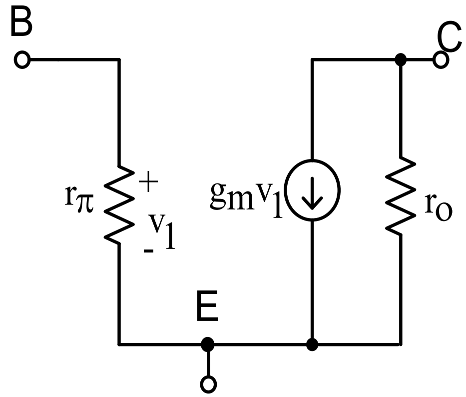
V_{OV} = 200 mV

$a_{v\_MOS} < a_{v\_BJT}$

(Do example page 182)

3.3.3 Common-Base configuration

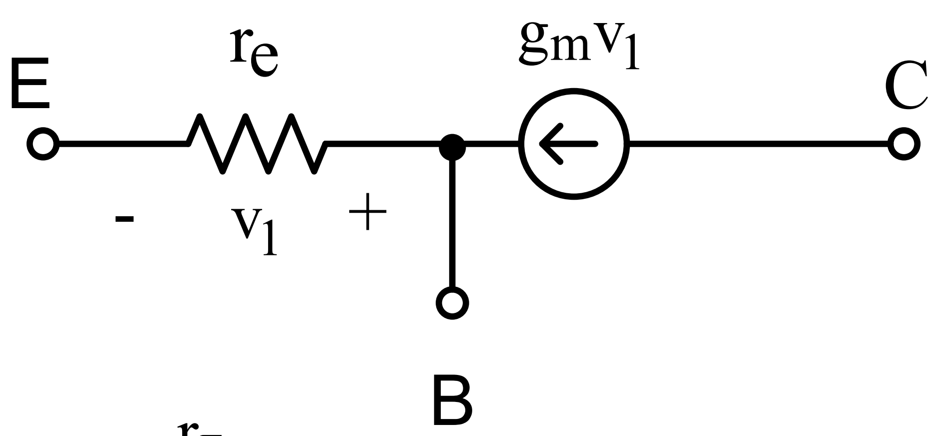




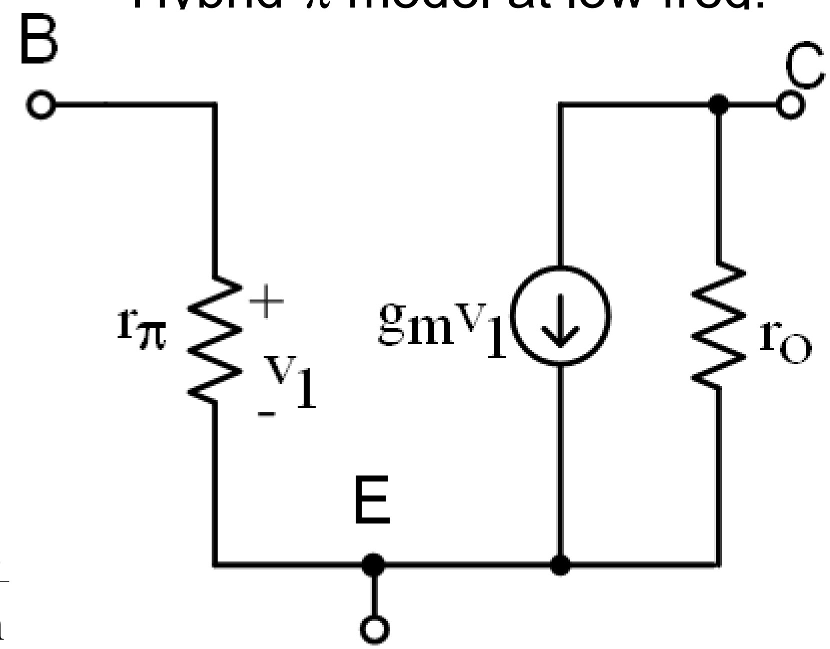
I/p signal applied to E. O/p taken from C. B tied to ac gnd.
The hybrid-π model provides an accurate representation of the small-signal behavior of the transistor independent of the circuit configuration. However, for the common-B, the hybrid-π model becomes tougher to analyze as the dependent current source is connected between the i/p and o/p terminals.

To simplify the analysis of a common-B (CB) amplifier, use a T-model instead.

The T-model at low freq:



Hybrid-π model at low freq:



$$r_e = \frac{r_\pi}{1 + g_m r_\pi}$$

$$r_\pi = \frac{\beta_o}{g_m}$$

$$r_e = \frac{r_\pi}{1 + g_m r_\pi} = \frac{\beta_o}{g_m\left(1 + g_m \frac{\beta_o}{g_m}\right)} = \frac{1}{g_m}\frac{\beta_o}{1 + \beta_o} = \frac{\alpha_o}{g_m}$$