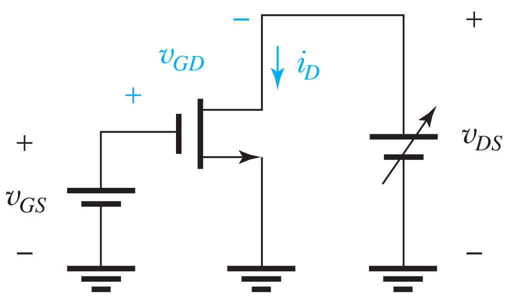
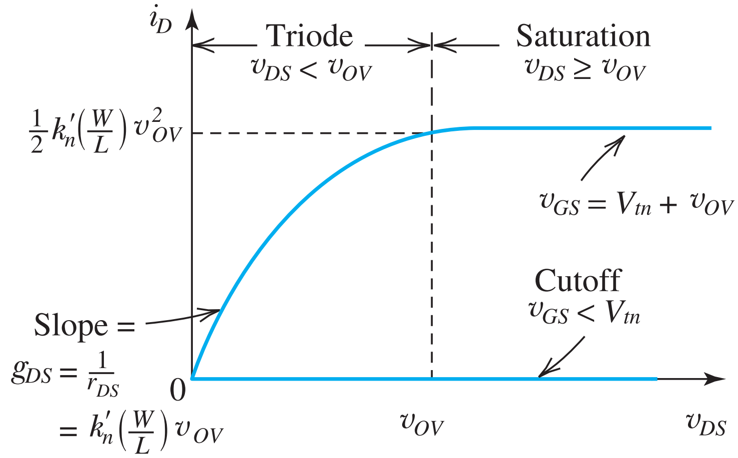
Table 5.1 Regions of Operation of the Enhancement NMOS Transistor





- $v_{GS} < V_{tn}$: no channel; transistor in cutoff; $i_D = 0$
- $v_{GS} = V_{tn} + v_{OV}$: a channel is induced; transistor operates in the triode region or the saturation region depending on whether the channel is continuous or pinched off at the drain end;

Triode Region	*Saturation Region*
Continuous channel, obtained by: $v_{GD} > V_{tn}$	Pinched-off channel, obtained by: $v_{GD} \leq V_{tn}$
or equivalently: $v_{DS} < v_{OV}$	or equivalently: $v_{DS} \geq v_{OV}$
Then, $i_D = k_n'\left(\frac{W}{L}\right)\left[(v_{GS} - V_{tn})v_{DS} - \frac{1}{2}v_{DS}^2\right]$	Then $i_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)(v_{GS} - V_{tn})^2$
or equivalently, $i_D = k_n'\left(\frac{W}{L}\right)\left(v_{OV} - \frac{1}{2}v_{DS}\right)v_{DS}$	or equivalently, $i_D = \frac{1}{2}k_n'\left(\frac{W}{L}\right)v_{OV}^2$

Table 6.2 Summary of the BJT Current–Voltage Relationships in the Active Mode

$$i_C = I_S e^{v_{BE}/V_T}$$

$$i_B = \frac{i_C}{\beta} = \left(\frac{I_S}{\beta}\right) e^{v_{BE}/V_T}$$

$$i_E = \frac{i_C}{\alpha} = \left(\frac{I_S}{\alpha}\right) e^{v_{BE}/V_T}$$

Note: For the *pnp* transistor, replace v_{BE} with v_{EB}.

$i_C = \alpha i_E$	$i_B = (1-\alpha) i_E = \dfrac{i_E}{\beta+1}$
$i_C = \beta i_B$	$i_E = (\beta+1) i_B$
$\beta = \dfrac{\alpha}{1-\alpha}$	$\alpha = \dfrac{\beta}{\beta+1}$

$V_T =$ thermal voltage $= \dfrac{kT}{q} \simeq 25$ mV at room temperature

Table 6.3 Simplified Models for the Operation of the BJT in DC Circuits

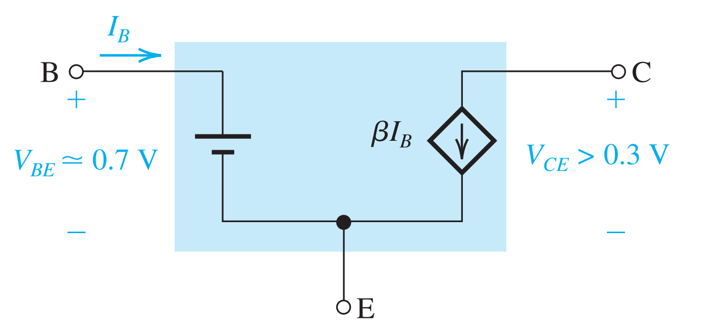
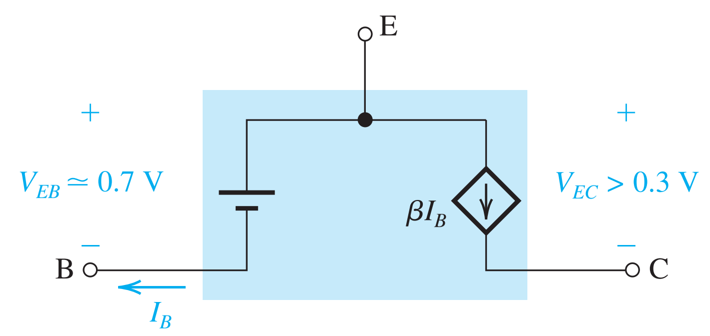
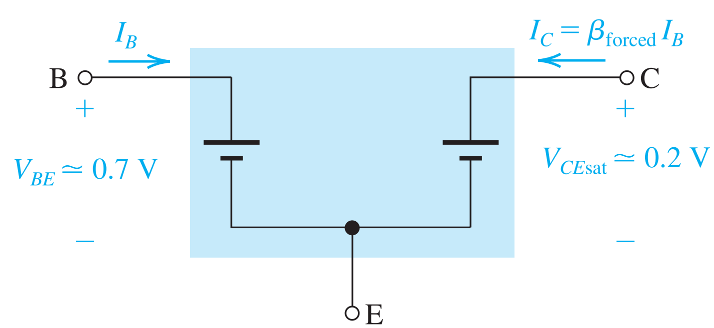
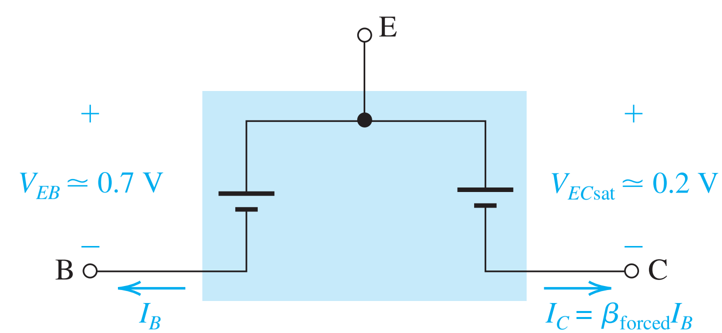
	npn	*pnp*
Active EBJ: Forward Biased CBJ: Reverse Biased		
Saturation EBJ: Forward Biased CBJ: Forward Biased		

Table 7.2 Small-Signal Models of the MOSFET

Small-Signal Parameters

NMOS transistors

- **Transconductance:**

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

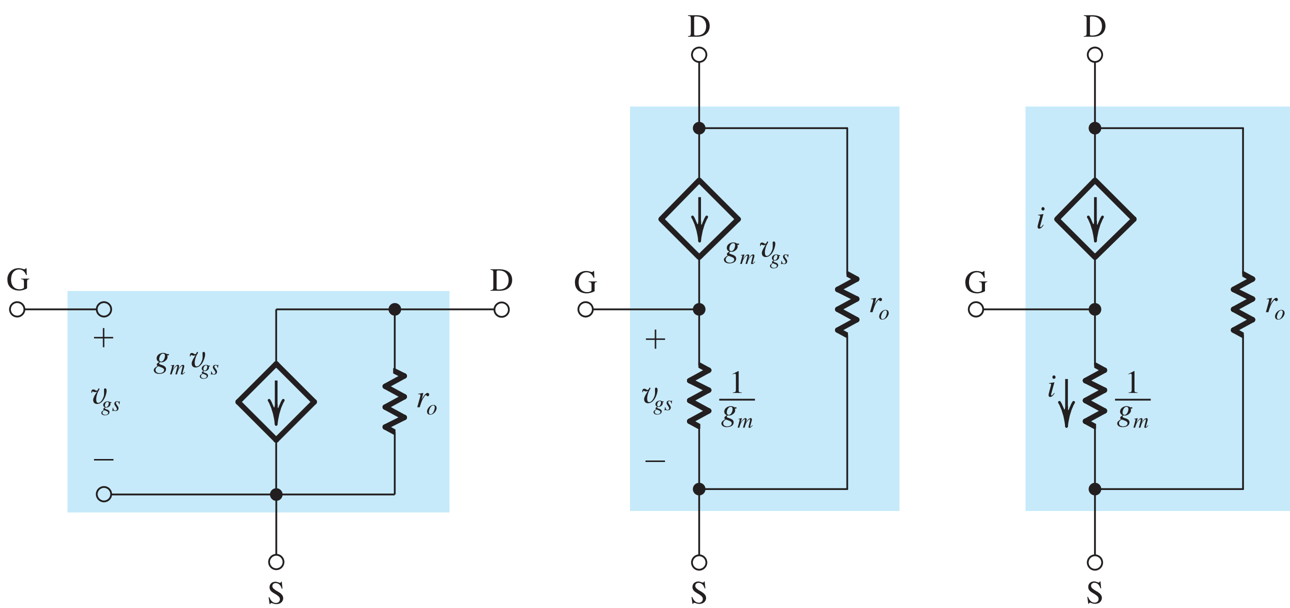
- Output resistance:

$$r_o = V_A / I_D = 1/\lambda I_D$$

PMOS transistors

Same formulas as for NMOS *except* using $|V_{OV}|$, $|V_A|$, $|\lambda|$ and replacing μ_n with μ_p.

Small-Signal, Equivalent-Circuit Models



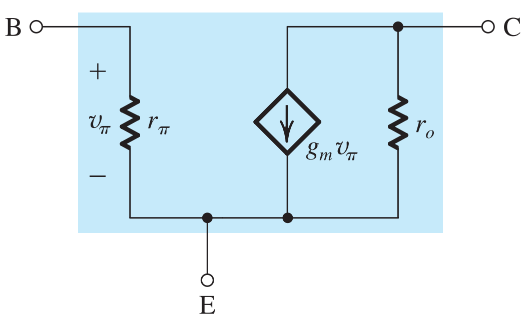
Hybrid-π model

T models

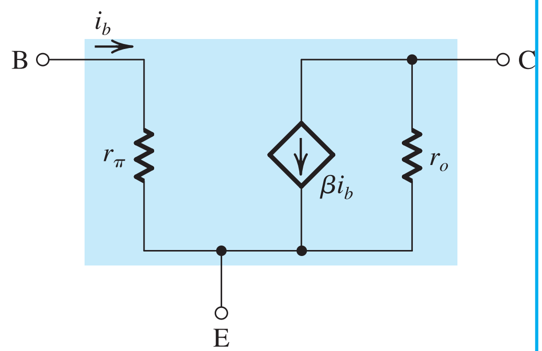
Table 7.3 Small-Signal Models of the BJT

Hybrid-π Model

- $(g_m v_\pi)$ Version

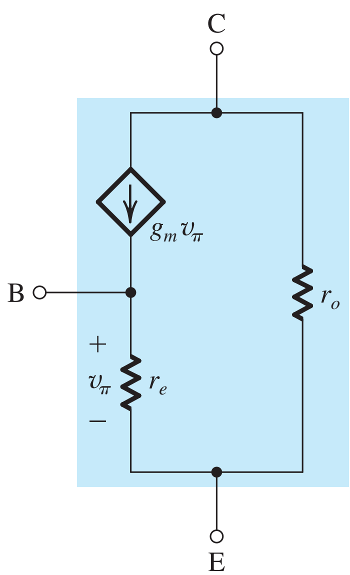


- (βi_b) Version

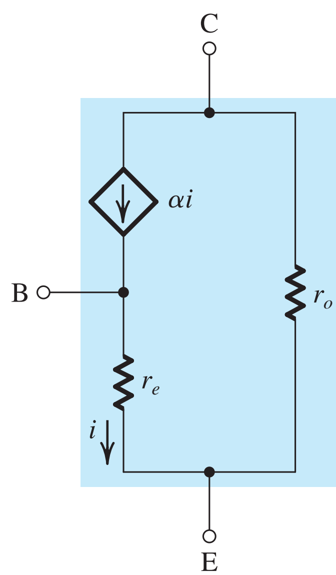


T Model

- $(g_m v_\pi)$ Version



- (αi) Version



Model Parameters in Terms of DC Bias Currents

$$g_m = \frac{I_C}{V_T} \qquad r_e = \frac{V_T}{I_E} = \alpha \frac{V_T}{I_C} \qquad r_\pi = \frac{V_T}{I_B} = \beta \frac{V_T}{I_C} \qquad r_o = \frac{|V_A|}{I_C}$$

In Terms of g_m

$$r_e = \frac{\alpha}{g_m} \qquad r_\pi = \frac{\beta}{g_m}$$

In Terms of r_e

$$g_m = \frac{\alpha}{r_e} \qquad r_\pi = (\beta + 1) r_e \qquad g_m + \frac{1}{r_\pi} = \frac{1}{r_e}$$

Relationships between α and β

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