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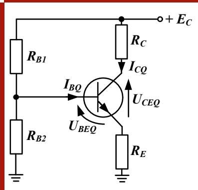
BJT amplifier
CE, CC, CB

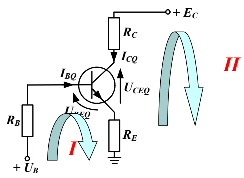
Q- point



Thevenin theorem

$$R_B = R_{B1} \| R_{B2}$$

$$U_B = E_C \frac{R_{B2}}{R_{B1} + R_{B2}}$$



Assumption:

$U_{BEQ} \approx 0{,}65V$

β

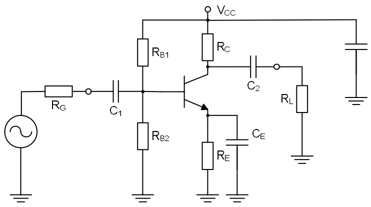
Q-point:

$$\left.\begin{aligned} z\quad I &\Rightarrow U_B = I_{BQ}R_B + I_{EQ}R_E + U_{BEQ} \\ z\quad II &\Rightarrow E_C = I_{EQ}R_E + U_{CEQ} + I_{CQ}R_C \\ I_{CQ} &= \beta I_{BQ} \\ I_{EQ} &= I_{CQ} + I_{BQ} \end{aligned}\right\} \Rightarrow \left\{\begin{aligned} I_{CQ} &= \beta I_{BQ} = \beta \frac{U_B - U_{BEQ}}{R_B + (\beta+1)R_E} \approx \frac{U_B - U_{BEQ}}{R_B/\beta + R_E} \\ U_{CEQ} &= E_C - I_{CQ}\left(R_E + \frac{\beta+1}{\beta}R_C\right) \underset{I_{EQ}\approx I_{CQ}}{\approx} E_C - I_{CQ}(R_E + R_C) \end{aligned}\right.$$

Q - point vs. application

Application	I_C(Q)	V_{CE}(Q) [V]
Low noise l.f. amps	20-200 [uA]	1-5
Small signal l.f. & h.f. amps	0.2-2 [mA]	3-10
High input impedance amps	0.1-10 [uA]	0.7-5
Broadband h.f. amps; low noise h.f	5-50 [mA]	5-10
Midium power l.f. amps	0.1 -10 [A]	5-15
High power l.f. amps	2-10 [A]	20-200
high power h.f. & special amps	2-10 [A]	20-1200

CE amplifier



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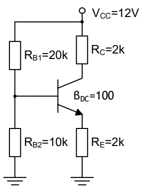
Potentiometric biasing - an example



$$V_{BB} = V_{CC}\frac{R_{B2}}{R_{B1}+R_{B2}} = 4V$$

$$R_B = R_{B1} \parallel R_{B2} = 6.66k$$

$$V_{BE} = 0.65V; \quad I_C \approx I_E; \quad I_C = \beta_{DC} I_B$$

$$I_E \approx I_C = \frac{V_{BB}-V_{BE}}{R_E + R_B/\beta_{DC}} = 1.62mA$$

$$V_{CE} = V_{CC} - R_C I_C - R_E I_E \approx V_{CC} - (R_C + R_E) I_C = 5.5V$$

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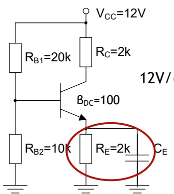
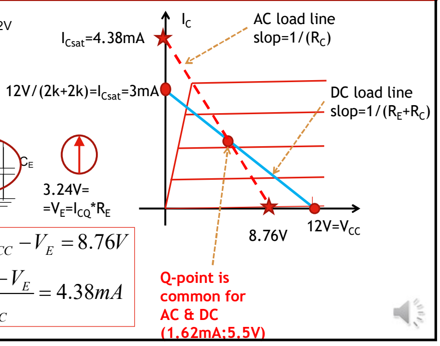
AC & DC load line

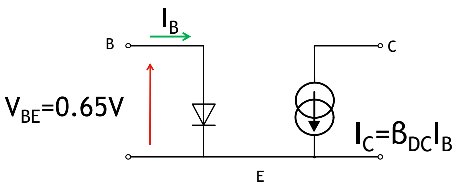




$$V_{CE(ACcutoff)} = V_{CC} - V_E = 8.76V$$

$$I_{C(ACsat)} = \frac{V_{CC}-V_E}{R_C} = 4.38mA$$

Ebers - Moll simplified model of BJT



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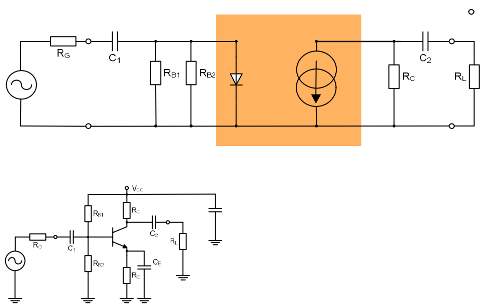
CE amp AC model



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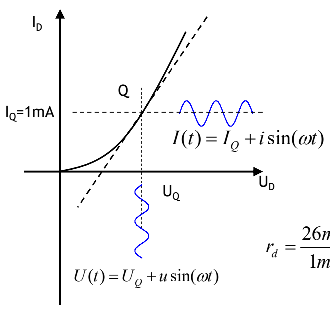
Diode - small signal dynamic resistance



$$I_D = I_S\left(\exp\left(\frac{U_D}{\phi_T}\right) - 1\right)$$

$$r_d = \left.\frac{dU_D}{dI_D}\right|_{I_D=I_Q} = \frac{\phi_T}{I_Q + I_s} \approx \frac{\phi_T}{I_Q}$$

$$r_d = \left.\frac{dU_D}{dI_D}\right|_{I_D=I_Q} \approx \frac{u}{i}$$

$$r_d = \frac{26mV}{1mA} = 26\Omega \quad for\ I_D = 1mA$$

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Diode - small signal dynamic resistance

$$r_d = \left.\frac{dU_D}{dI_D}\right|_{I_D=I_Q} = \frac{\phi_T}{I_D + I_s} \approx \frac{\phi_T}{I_D}$$

$$r_d = \frac{26mV}{I_D} = \frac{26mV}{1mA} = 26\Omega \quad for\ I_D = 1mA;\ n = 1$$

$$r_d = \frac{26mV}{0.1mA} = 260\Omega \quad for\ I_D = 100\mu A;\ n = 1$$

$$r_d = \frac{26mV}{10\mu A} = 2.6k\Omega \quad for\ I_D = 10\mu A;\ n = 1$$

HINT:

The linear model is satisfactory for amplitudes up to 25mV

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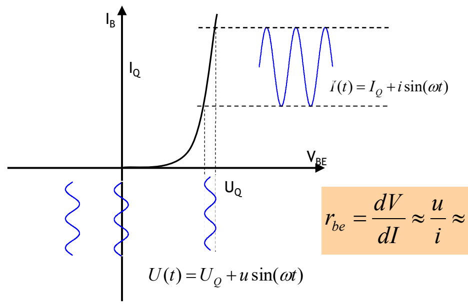
Diode - small signal dynamic resistance



$$r_{be} = \frac{dV}{dI} \approx \frac{u}{i} \approx \frac{\varphi_T}{I_B}$$

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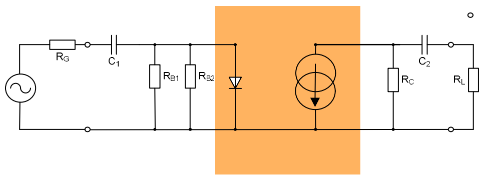
CE amp model



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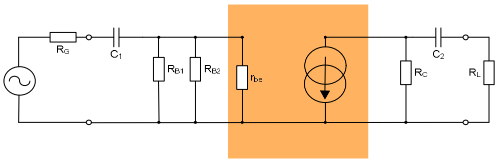
CE BJT amp



$$r_{be} = \frac{dV}{dI} \approx \frac{u}{i} \approx \frac{\varphi_T}{I_B}$$

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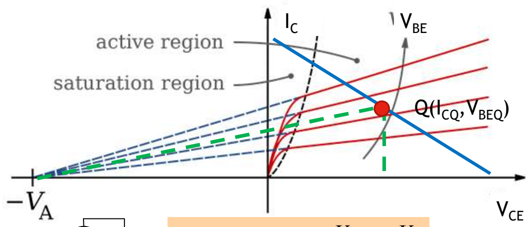
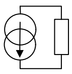
Early voltage; establishing of r_{ce}





$$r_{ce} = \frac{dV_{CE}}{dI_C} \approx \frac{u}{i} \approx \frac{V_{CEQ} + V_A}{I_{CQ}}$$

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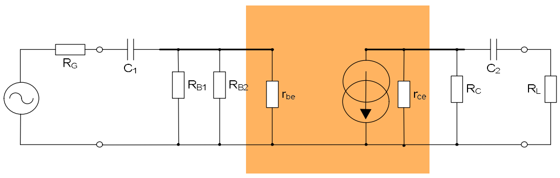
CE amp BJT model



$$r_{ce} = \frac{dV_{CE}}{dI_C} \approx \frac{u}{i} \approx \frac{V_{CEQ} + V_A}{I_{CQ}}$$

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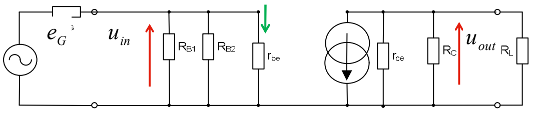
CE amp BJT model for midium frequencies

$$g_m = \frac{i_C}{u_{be}}$$

$$i_B = \frac{u_{be}}{r_{be}}$$

$$i_C = \beta_{AC} i_B$$



$$i_C = \beta_{AC}\frac{u_{be}}{r_{be}} = \frac{\beta_{AC}}{r_{be}}u_{be} = g_m u_{be} = g_m u_{in}$$

$$g_m = \frac{\beta_{AC}}{r_{be}} = \frac{I_{CQ}}{\varphi_T}$$

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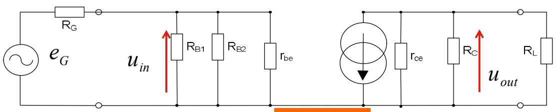
CE amp BJT model for midium frequencies



$$u_{in} = e_G \frac{(r_{be} \| R_B)}{(r_{be} \| R_B) + R_G}$$

$$i_c = g_m u_{in}$$

$$u_{out} = -i_c (r_{ce} \| R_C \| R_L)$$

$$\frac{u_{out}}{e_G} = -\frac{u_{in}}{e_G}\frac{i_c}{u_{in}}\frac{u_{out}}{i_c} = \underbrace{-\frac{(r_{be} \| R_B)}{(r_{be} \| R_B) + R_G} g_m (r_{ce} \| R_C \| R_L)}_{A_{Veffective}}$$

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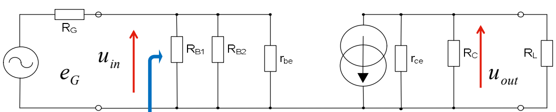
CE amp BJT model for medium frequencies



$$r_{in} = (r_{be} \| R_{B1} \| R_{B2})$$

$$r_{be} = \frac{\varphi_T}{I_{BQ}} = \frac{\varphi_T}{I_{CQ}}\beta_{AC}$$

$$g_m = \frac{\beta_{AC}}{r_{be}} = \frac{I_{CQ}}{\varphi_T}$$

$$\frac{u_{out}}{e_G} = \underbrace{-\underbrace{\frac{r_{in}}{r_{in} + R_G}}_{\gamma}\underbrace{g_m \underbrace{(r_{ce} \| R_C \| R_L)}_{R_{LOAD}}}_{A_V}}_{A_{Veffective}}$$

Watch please the video with example of CE amplifier analysis

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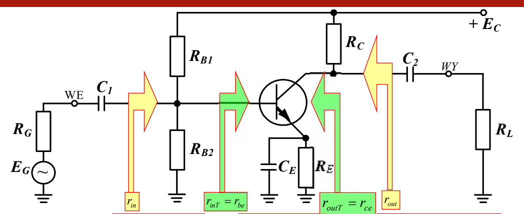
Summary of CE amp BJT
medium frequencies



$r_{in} = \underbrace{R_{B1} \| R_{B2}}_{R_B} \| r_{be}$

$r_{out} = r_{ce} \| R_C \underset{r_{ce} >> R_C}{\approx} R_C$

$\varphi_T \approx 26mV$
$V_A \approx 50 \div 300V$
$U_{CEQ}, I_{CQ} - \text{Q} - po\text{int}$
$\beta_{AC} \approx \beta_{DC}$

$g_m = \frac{I_{CQ}}{\varphi_T}$
$r_{be} = \frac{\beta}{g_m}$
$r_{ce} = \frac{V_A + U_{CEQ}}{I_{CQ}}$

$$k_{Veff} = \underbrace{-g_m \cdot \underbrace{R_{LOAD}}_{R_L \| r_{out}}}_{k_V} \cdot \underbrace{\gamma_V}_{\frac{r_{in}}{r_{in}+R_G}}$$

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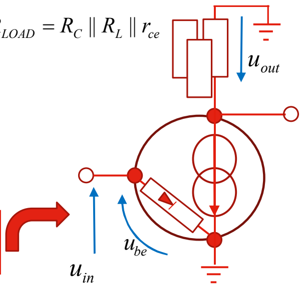
CE amp
simple approach

$g_m = \frac{I_{CQ}}{\varphi_T}$

$r_{be} = \frac{\beta}{g_m}$

$R_{LOAD} = R_C \| R_L \| r_{ce}$



$r_{inT} = \frac{u_{in}}{i_B} = r_{be} = \frac{\varphi_T}{I_{BQ}}$

$r_{in} = R_{B1} \| R_{B2} \| r_{inT}$

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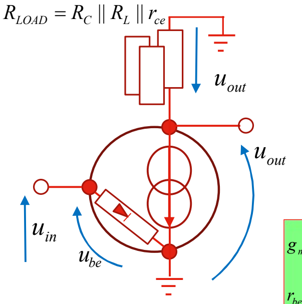
CE amp simple approach

$R_{LOAD} = R_C \parallel R_L \parallel r_{ce}$



$$\begin{cases} i_C = g_m u_{be} \\ u_{out} = -i_C R_{LOAD} \end{cases}$$

$$A_V = \frac{u_{out}}{u_{in}} = -g_m R_{LOAD}$$

$$g_m = \frac{I_{CQ}}{\varphi_T}$$

$$r_{be} = \frac{\beta}{g_m}$$

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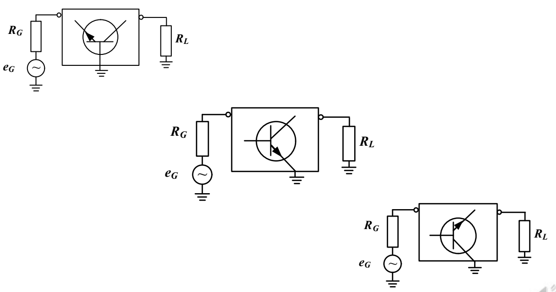
CB CE CC



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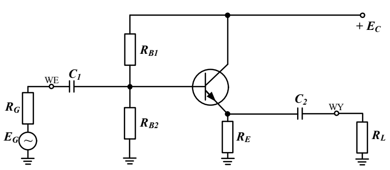
CC amplifier



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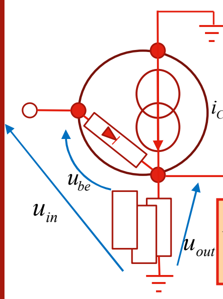
CC - emiter follower



$$\begin{cases} i_C = g_m u_{be} \\ u_{out} \approx i_C R_{LOAD} \\ u_{in} = u_{be} + u_{out} \end{cases}$$

$$A_V = \frac{u_{out}}{u_{in}} = \frac{R_{LOAD}}{R_{LOAD} + \frac{1}{g_m}} = \frac{R_{LOAD}}{R_{LOAD} + \frac{\varphi_T}{I_{CQ}}} \approx< 1$$

$$R_{LOAD} = R_E \parallel R_L \parallel r_{ce}$$

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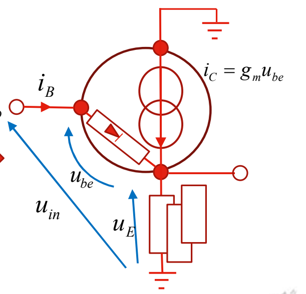
CC - emitter follower

$$\begin{cases} u_{be} = i_B r_{be} = \frac{i_C}{\beta} r_{be} \\ u_E = i_E R_{LOAD} \approx i_C R_{LOAD} \\ u_{in} = u_{be} + u_E = i_B r_{be} + \underbrace{\beta i_B}_{i_E} R_{LOAD} \end{cases}$$

$$r_{inT} = \frac{u_{in}}{i_B} = r_{be} + \beta R_{LOAD}$$



$$R_{LOAD} = R_E \parallel R_L \parallel r_{ce}$$

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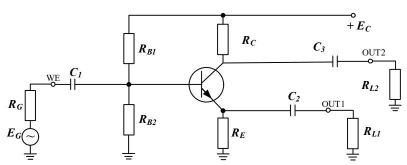

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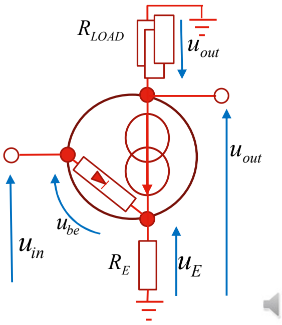
AC emitter feedback

$$u_{in} = u_{be} + u_E = i_B r_{be} + \underbrace{i_B \beta}_{i_E} R_E$$

$$r_{inT} = \frac{u_{in}}{i_B} = r_{be} + \beta R_E$$



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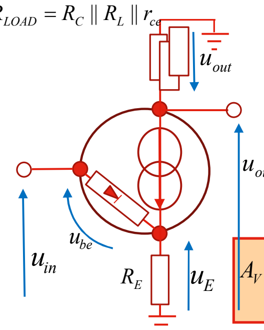
AC emitter feedback

$$R_{LOAD} = R_C \parallel R_L \parallel r_{ce}$$



$$\begin{cases} i_C = g_m u_{be} \\ u_{in} = u_{be} + u_E \\ u_E = i_C R_E = \dfrac{R_E}{R_E + 1/g_m} u_{in} \\ u_{out} = -i_C R_{LOAD} = \dfrac{-R_{LOAD}}{R_E + 1/g_m} u_{in} \end{cases}$$

$$A_V = \frac{u_{out}}{u_{in}} = -\frac{R_{LOAD}}{R_E + 1/g_m} \approx -\frac{R_{LOAD}}{R_E}$$

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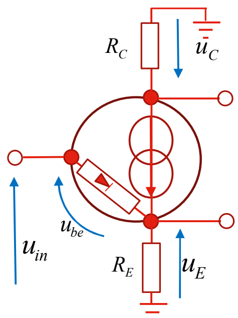
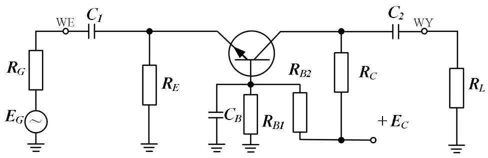
2 outputs emitter feedback amp



$$A_{VC} = \frac{u_C}{u_{in}} = -\frac{R_C}{R_E + 1/g_m} \approx -\frac{R_C}{R_E}$$

$$A_{VE} = \frac{u_E}{u_{in}} = \frac{R_E}{R_E + 1/g_m} \approx 1$$



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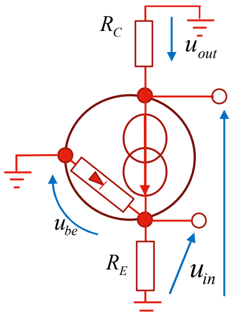
CB - simple approach



$$\begin{cases} i_C = g_m u_{be} \\ u_{out} = -i_C R_C \\ u_{in} = -u_{be} \end{cases}$$

$$k_u = \frac{u_{out}}{u_{in}} = g_m R_C$$

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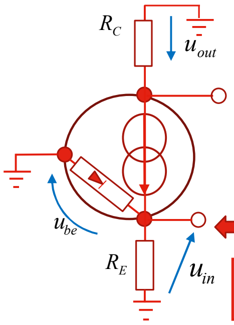
CB - simple approach



$$\begin{cases} i_E = -g_m u_{be} + \frac{u_{in}}{R_E} \\ u_{in} = -u_{be} \\ g_m = \frac{1}{r_{be}/\beta} = \frac{\beta}{r_{be}} \end{cases}$$

$$r_{in} = \frac{u_{in}}{i_E} = \frac{r_{be}}{\beta} \| R_E = \frac{1}{g_m} \| R_E$$

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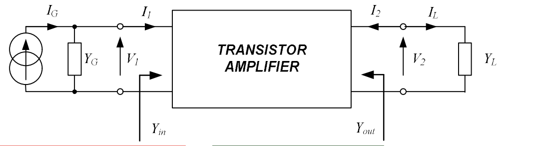
y_{xx} and h_{xx} parameters



$$\begin{bmatrix} I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} y_{11} & y_{12} \\ y_{21} & y_{22} \end{bmatrix} \begin{bmatrix} V_1 \\ V_2 \end{bmatrix}$$

$$r_{be} = h_{11} = h_{ie} = \frac{1}{y_{11}}$$

$$g_m = y_{21}$$

$$\begin{bmatrix} V_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} h_{11} & h_{12} \\ h_{21} & h_{22} \end{bmatrix} \begin{bmatrix} I_1 \\ V_2 \end{bmatrix}$$

$$\beta = h_{21} = h_{fe} = \frac{y_{21}}{y_{11}}$$

$$r_{ce} = \frac{1}{h_{22}} = \frac{1}{y_{22}}$$

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CE-CC-CB comparison

$R_B = R_{B1} \parallel R_{B2} \quad r_{be} / \beta = 1 / g_m$

Para-meter	configuration		
	CE	CC	CB
$A_V = \frac{u_{be}}{u_L}$	$-\beta \frac{R_C \parallel R_L \parallel r_{ce}}{r_{be}}$	$\frac{R_E \parallel R_L \parallel r_{ce}}{R_E \parallel R_L \parallel r_{ce} + r_{be}/\beta}$	$-\beta \frac{R_C \parallel R_L \parallel r_{ce}}{r_{be}}$
$A_I = \frac{i_b}{i_L}$	$\frac{-R_C \parallel r_{ce}}{R_C \parallel r_{ce} + R_L}\beta$	$\frac{R_E}{R_E + R_L}\beta$	$\frac{-R_C \parallel r_{ce}}{R_C \parallel r_{ce} + R_L}$
$r_{in} = \frac{u_{be}}{i_{b(e)}}$	$R_B \parallel r_{be}$	$(\beta(R_E \parallel R_L) + r_{be}) \parallel R_B$	$\left(\frac{r_{be}}{\beta}\right) \parallel R_E$
$r_{out} = \frac{u_{out}}{i_{c(e)}}$ (e) - for CB	$R_C \parallel r_{ce}$	$\left(\frac{(R_B \parallel R_G) + r_{be}}{\beta}\right) \parallel R_E$	$R_C \parallel r_{ce}$

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CE-CC-CB general comparison

Para-meter	configuration		
	CE	CC	CB
$A_V = \frac{u_{be}}{u_L}$	***High*** *(10-200)*	***<1***	***High*** *(10-200)*
$A_I = \frac{i_b}{i_L}$	***High*** *(10-200)*	***High*** *(10-200)*	***<1***
$r_{in} = \frac{u_{be}}{i_{b(e)}}$	***Medium*** *(0.5k-5k)*	***High*** *(10k-1M)*	***Low*** *(10Ω-500Ω)*
$r_{out} = \frac{u_{out}}{i_{c(e)}}$ (e) - for CB	***Medium*** *(0.5k-5k)*	***Low*** *(10Ω-500Ω)*	***Medium*** *(0.5k-5k)*

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Summary

- AC vs. DC load line
- Ebers – Moll BJT model
- linear transistor model
- voltage gain, effective voltage gain
- CE, CC, CB amps parameters

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Problems

- **Estimate voltage gain and effective voltage gain for given diagram of BJT CE amplifier (known parameters: R_g,R_{B1},R_{B2}, R_C, R_L, β, φ_T, I_{CQ}, U_{CEQ}).**
- **What is the „emitter follower" and what characteristic parameters it has ?**
- *Compare BJT amplifier in CE, CB, CC configurations.*