EE210: Microelectronics-I

Lecture-35
Review of BJT Circuits-part-1

https://youtu.be/y6nPaUIdzF8

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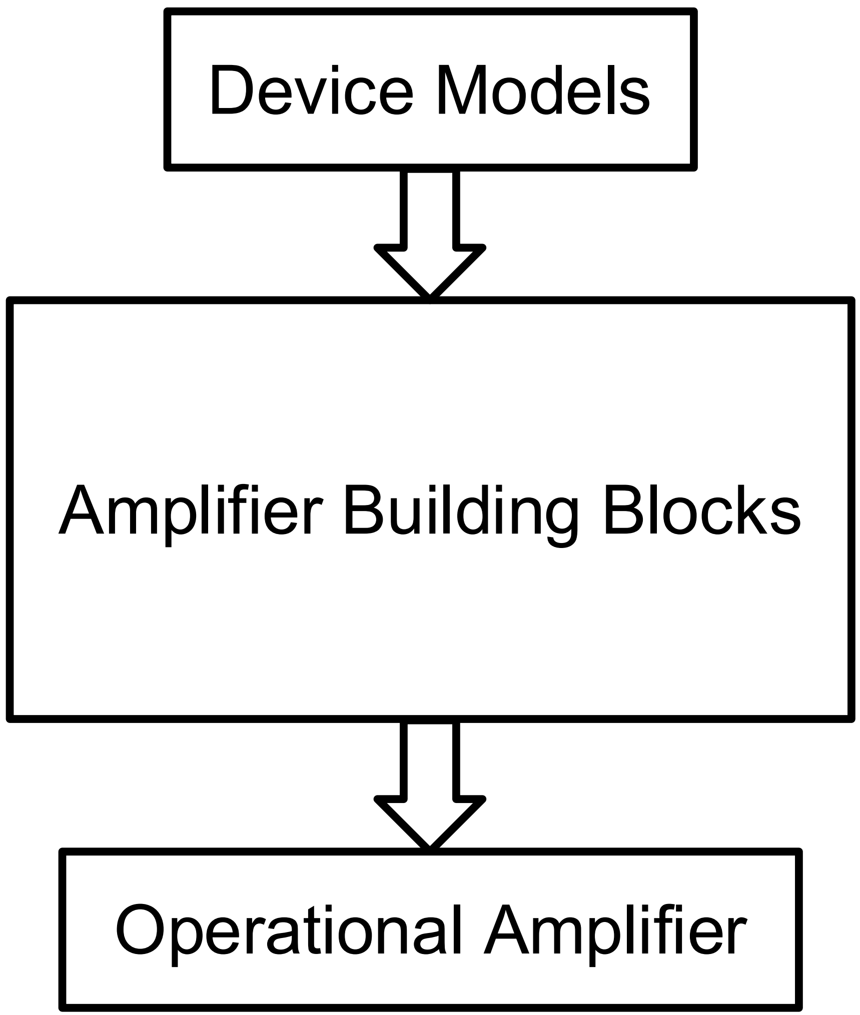
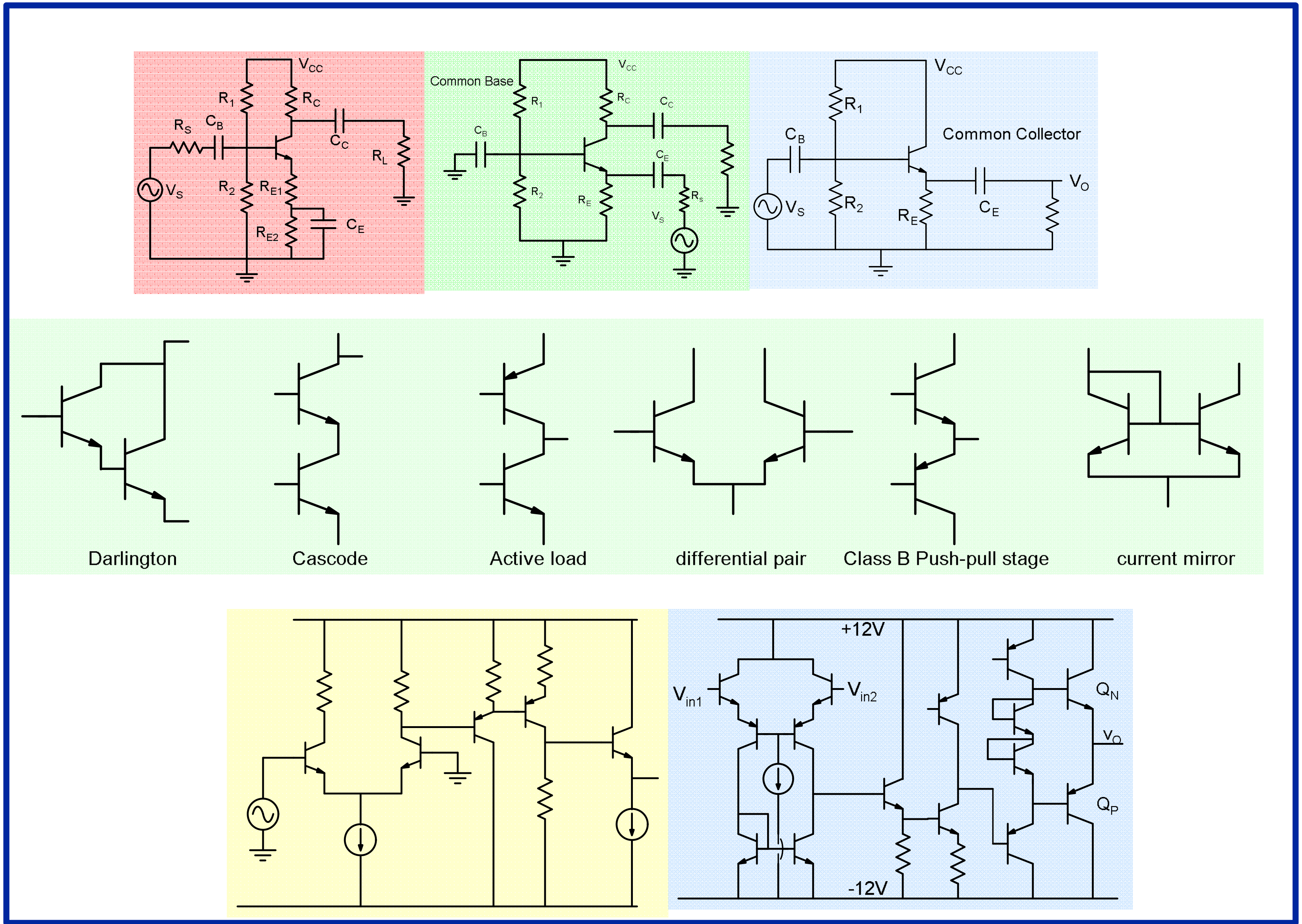
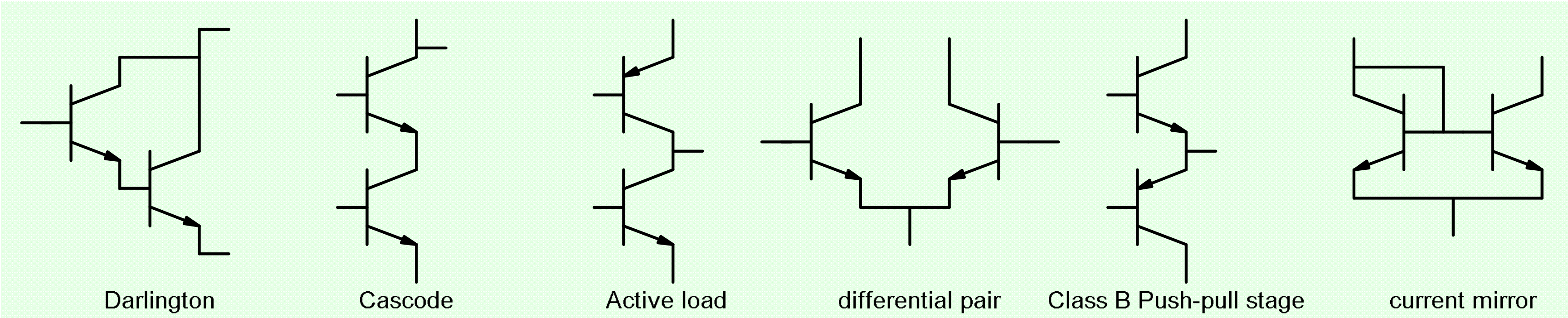
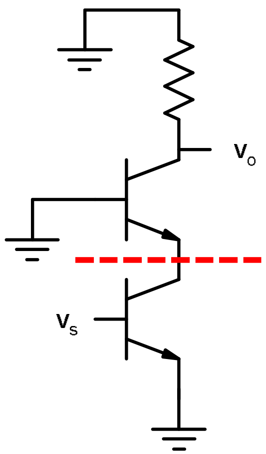
EE210


Device Models
Amplifier Building Blocks
Operational Amplifier

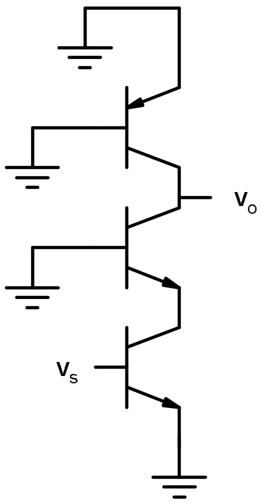
EE210: Overview



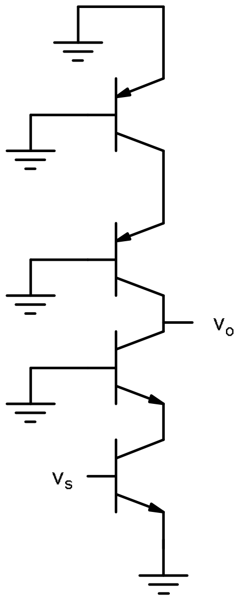




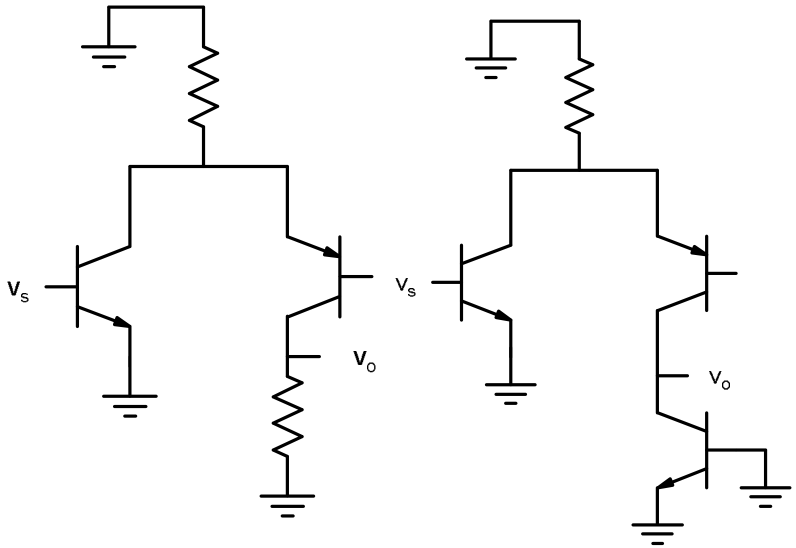
Cascode with resistive load



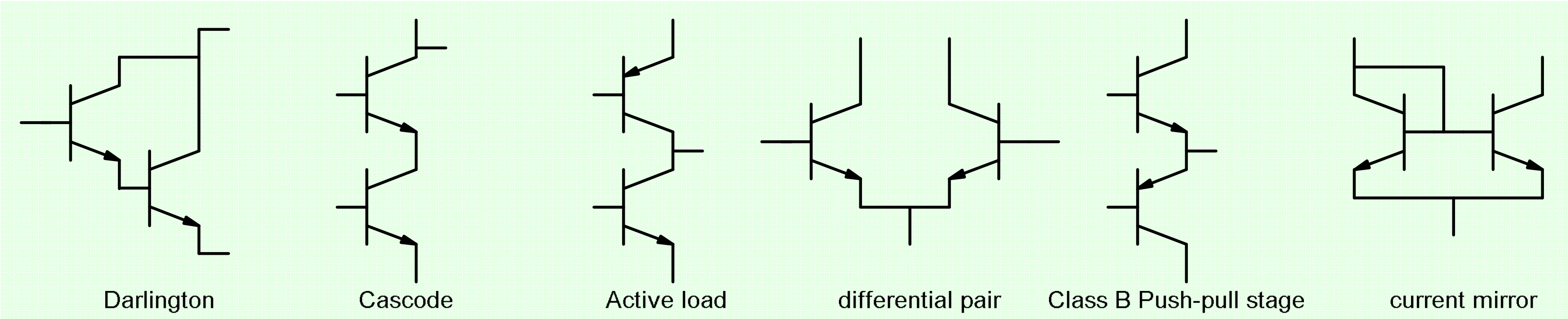
Cascode with active load

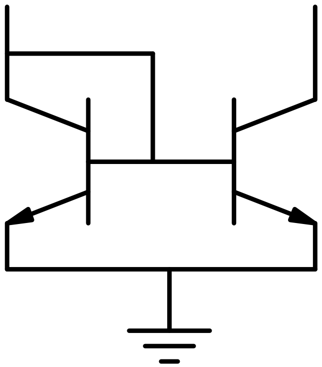


Cascode with cascode load

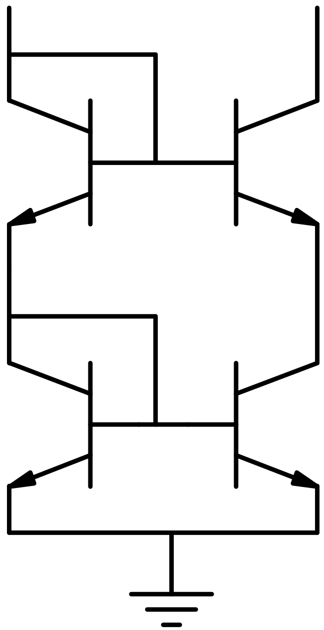


Folded cascode

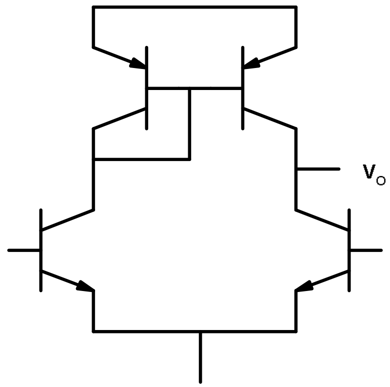




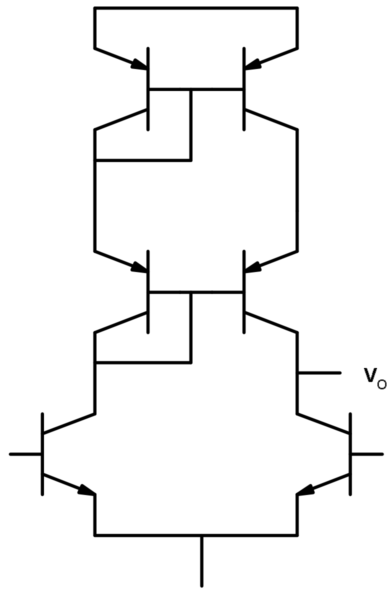
Simple Current Mirror



Cascode
Current Mirror



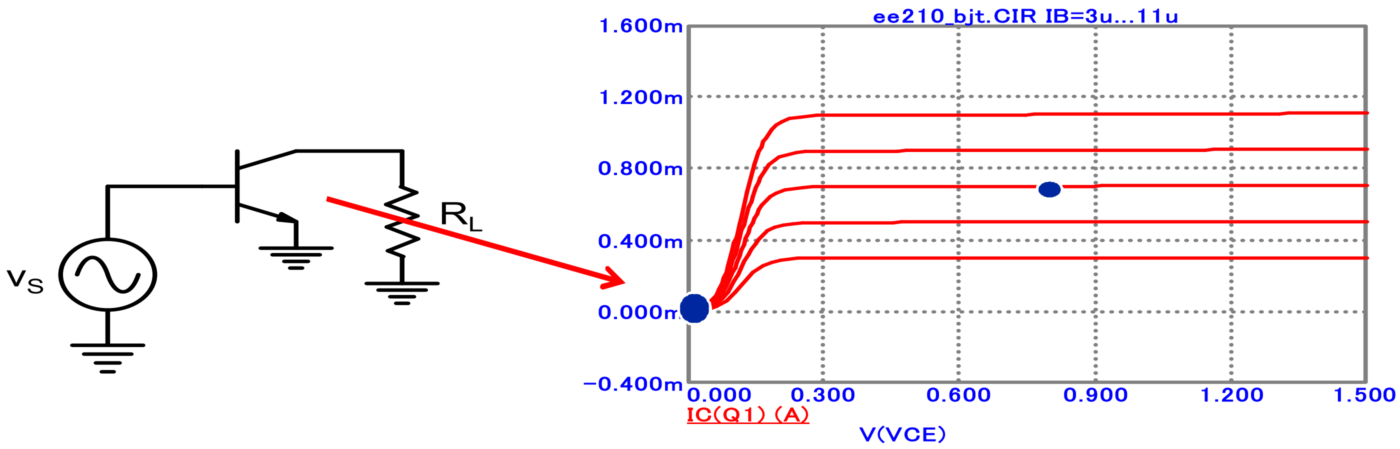
Diff. amp with
Current Mirror
load

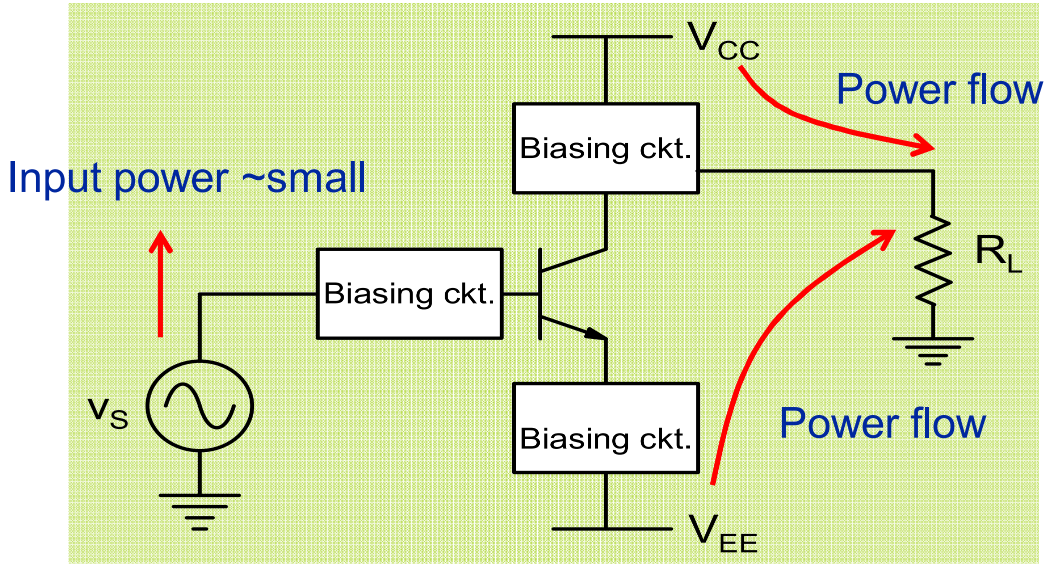


Diff. amp with cascode
Current Mirror load

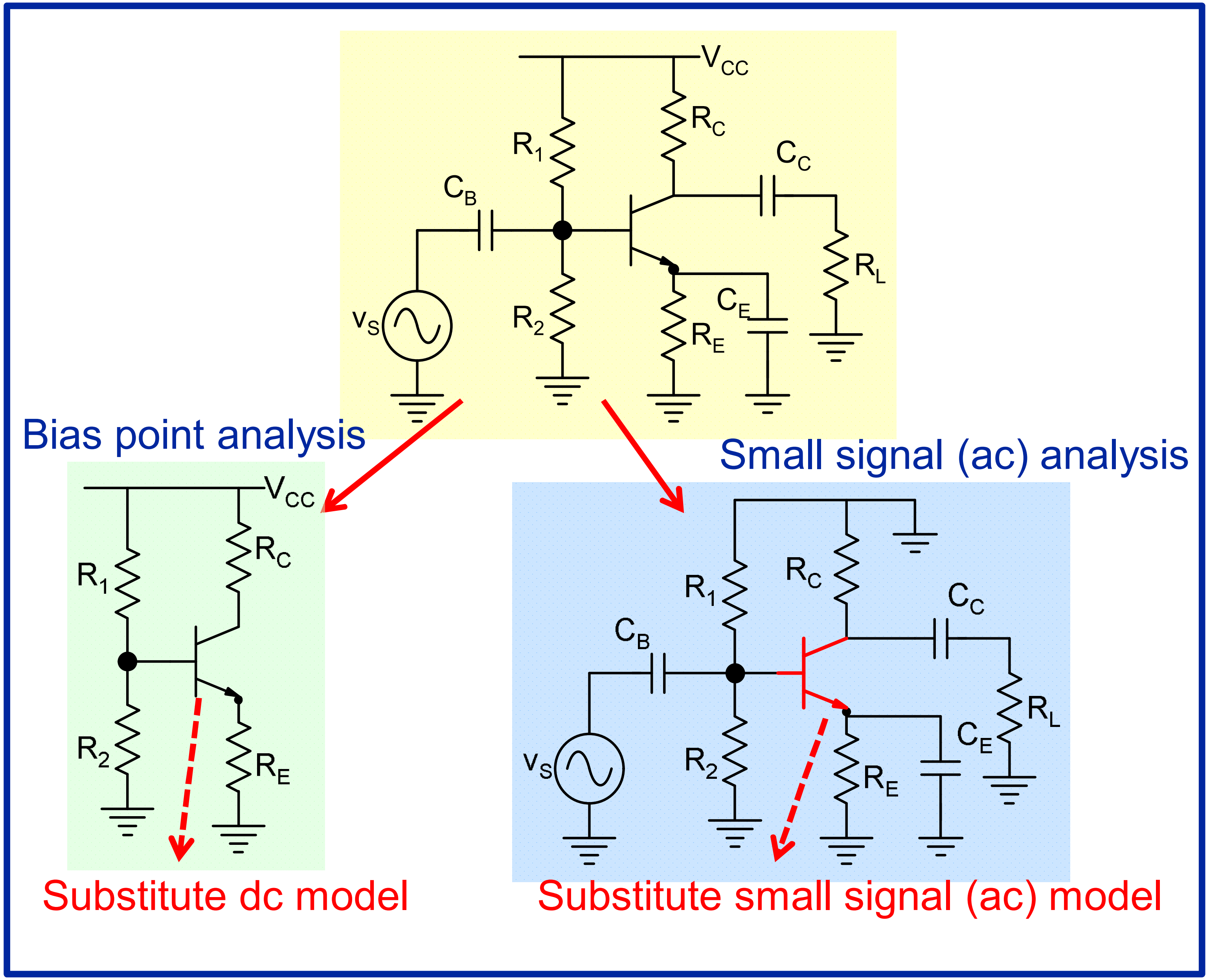
Review

A Transistor needs to be biased in active region to amplify



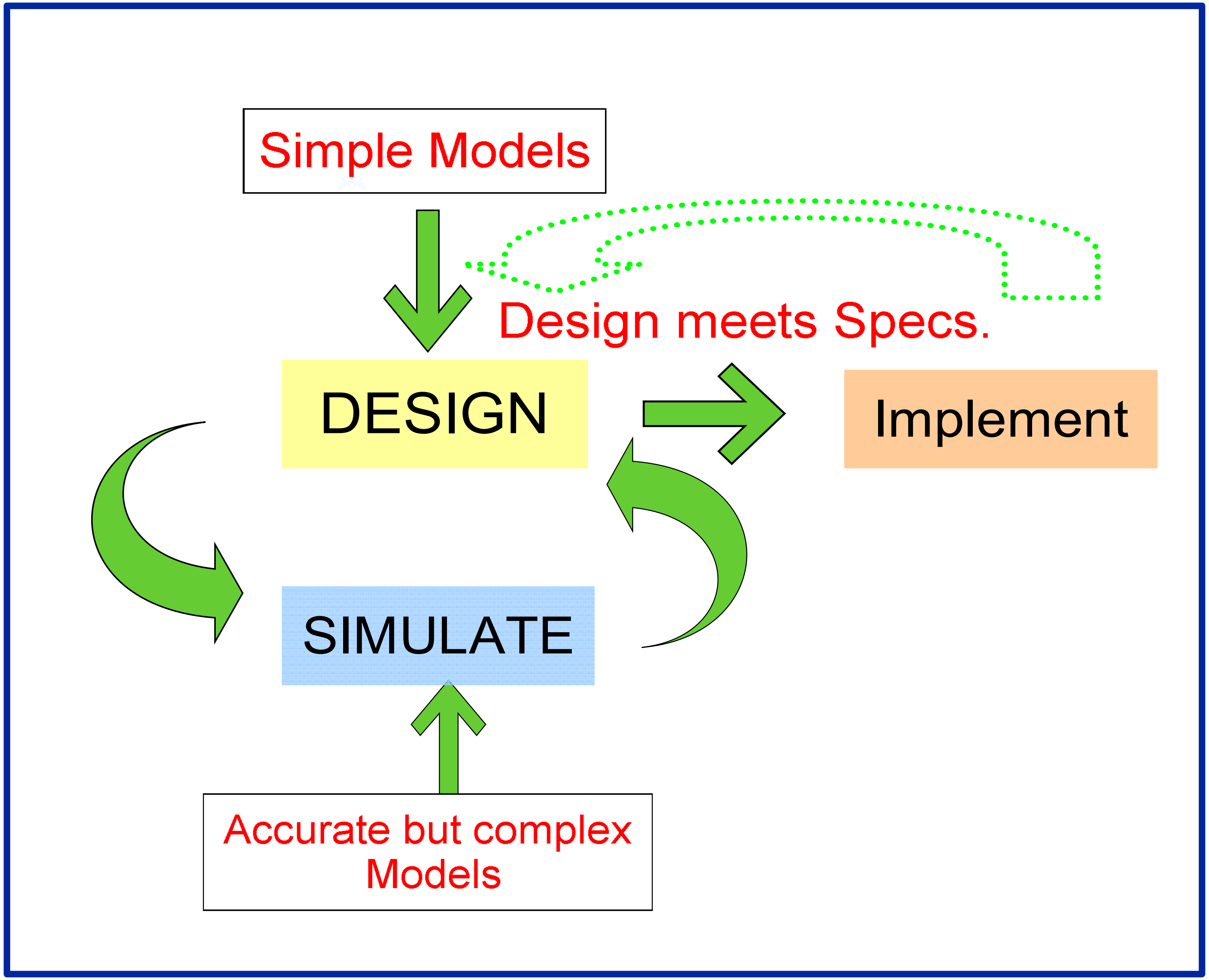


Analysis

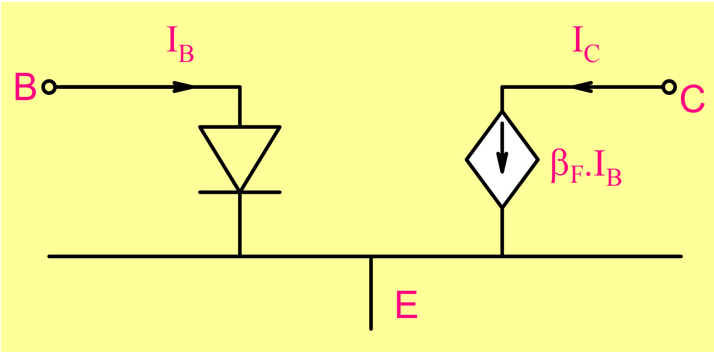


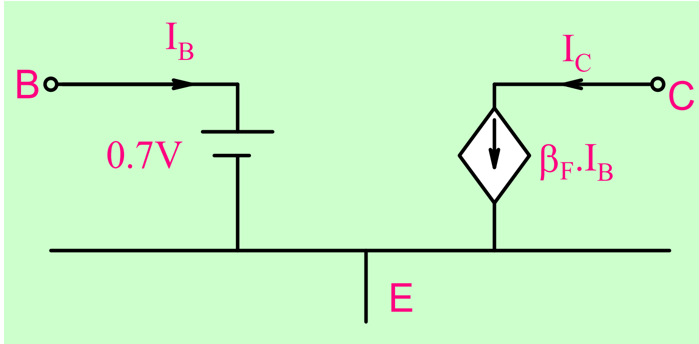
V_{CC}
R_1
R_C
C_C
C_B
R_L
C_E
v_S
R_2
R_E
Bias point analysis
Small signal (ac) analysis
V_{CC}
R_C
R_1
R_2
R_E
R_C
R_1
C_C
C_B
R_L
C_E
v_S
R_2
R_E
Substitute dc model
Substitute small signal (ac) model

Role of simple model in design cycle



Model Of An NPN BJT In Forward Active Mode





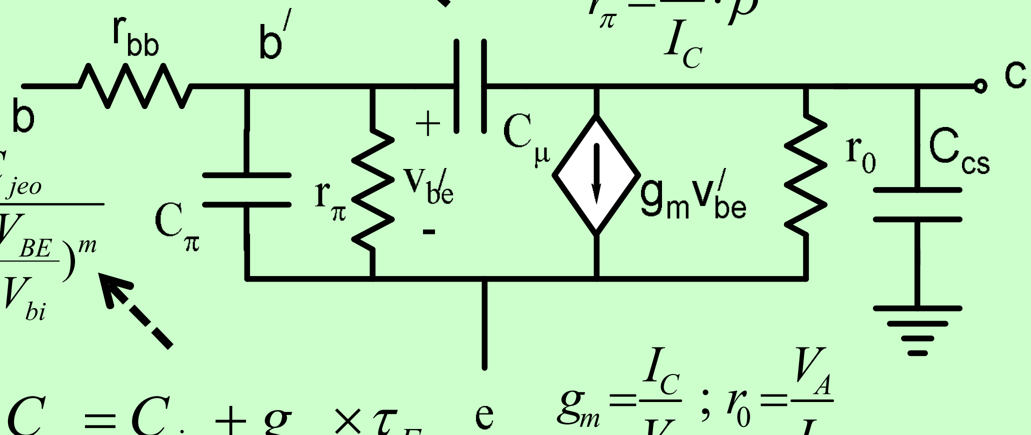
$$I_C = I_S\left(\exp\left(\frac{V_{BE}}{V_T}\right)-1\right)\left(1+\frac{V_{CE}}{V_A}\right)$$

$$I_B = \frac{I_S\left(\exp\left(\frac{V_{BE}}{V_T}\right)-1\right)}{\beta_F}$$

$$I_C = \beta_F I_B\left(1+\frac{V_{CE}}{V_A}\right)$$

$$C_\mu = C_{jc} = \frac{C_{jco}}{\left(1-\frac{V_{BC}}{V_{bi}}\right)^m}$$

$$r_\pi = \frac{V_T}{I_C}\cdot\beta$$

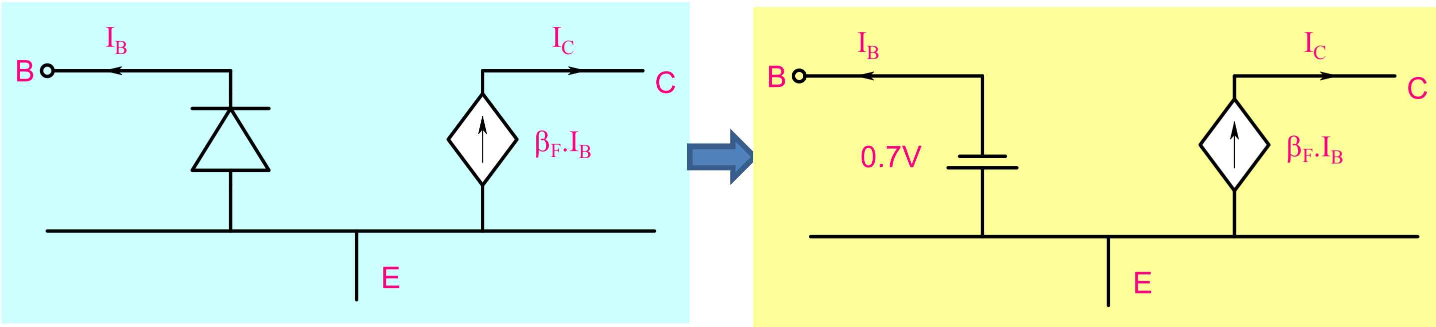


$$C_{je} = \frac{C_{jeo}}{\left(1-\frac{V_{BE}}{V_{bi}}\right)^m}$$

$$C_\pi = C_{je} + g_m \times \tau_F$$

$$g_m = \frac{I_C}{V_T}\,;\; r_0 = \frac{V_A}{I_C}$$

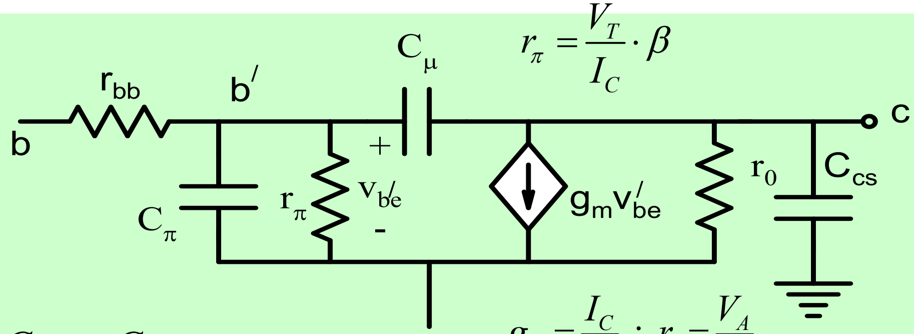
Model of a PNP BJT In Forward Active Mode



$$I_C = I_S\left(\exp(\frac{V_{EB}}{V_T}) - 1\right)\left(1 + \frac{V_{EC}}{V_A}\right)$$

$$I_B = \frac{I_S\left(\exp(\frac{V_{EB}}{V_T}) - 1\right)}{\beta_F}$$

$$I_C = \beta_F\, I_B\left(1 + \frac{V_{EC}}{V_A}\right)$$

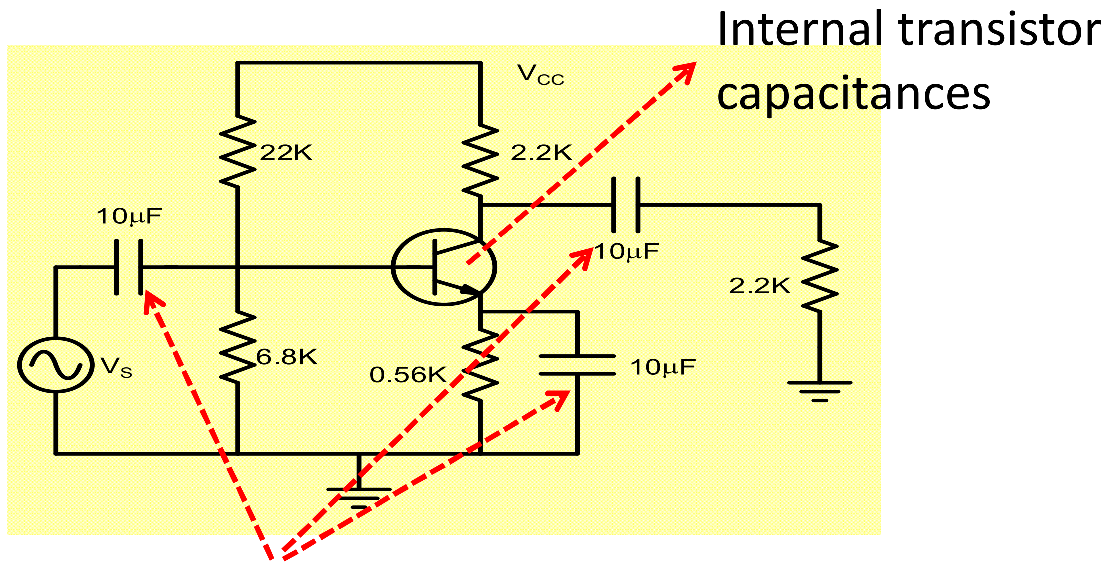


$$r_\pi = \frac{V_T}{I_C}\cdot\beta$$

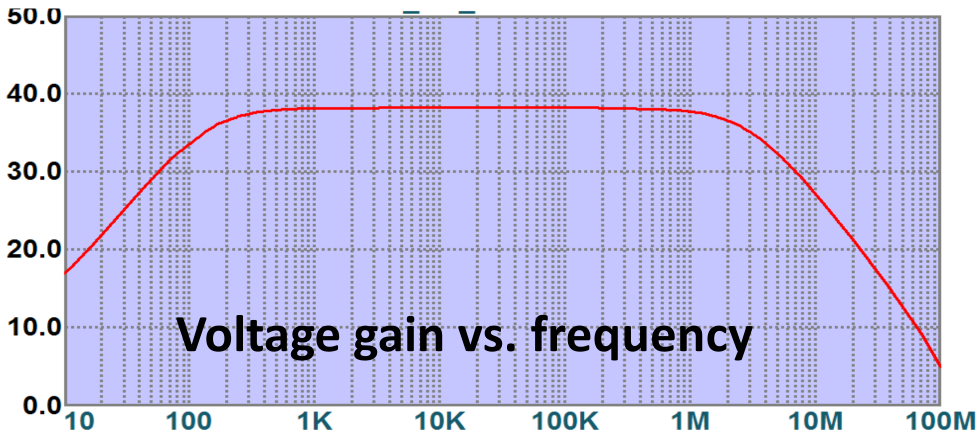
$$C_\pi = C_{je} + g_m \times \tau_F$$

$$g_m = \frac{I_C}{V_T}\ ;\ r_0 = \frac{V_A}{I_C}$$

Characteristics of Amplifiers Are Frequency Dependent



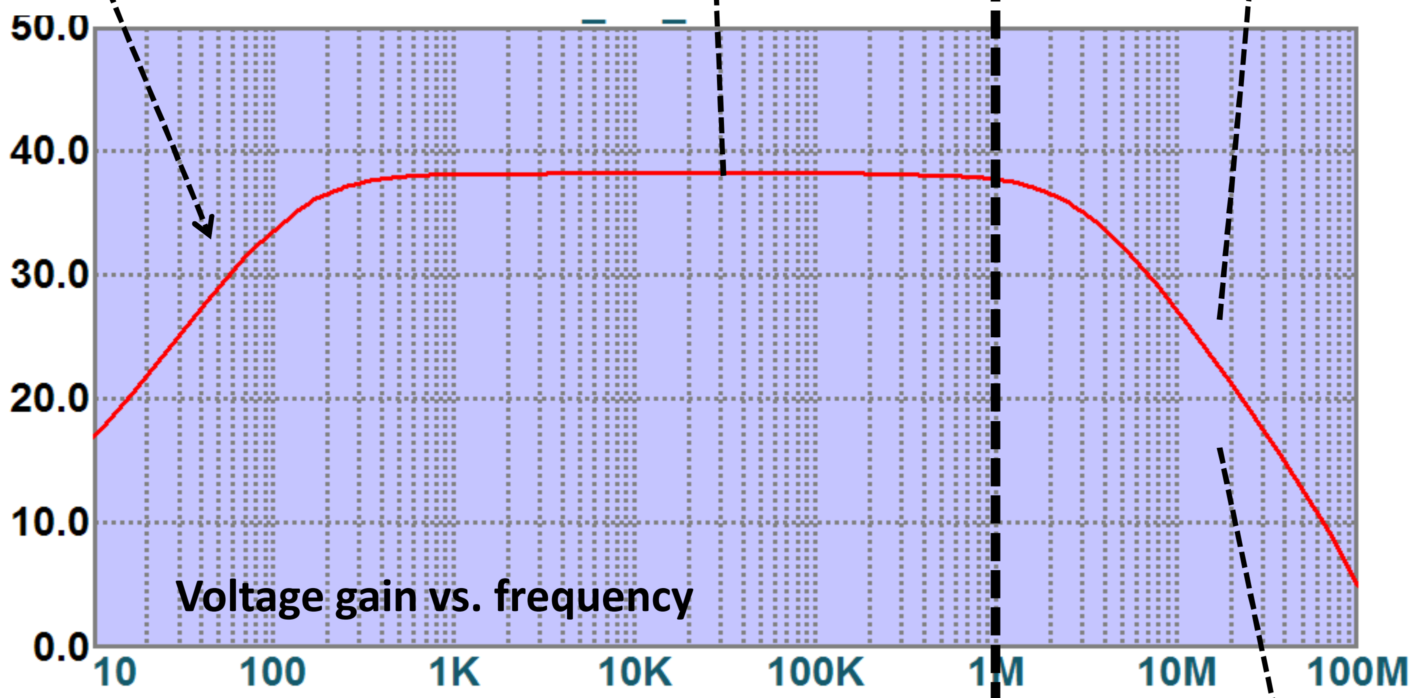
External coupling and bypass capacitors

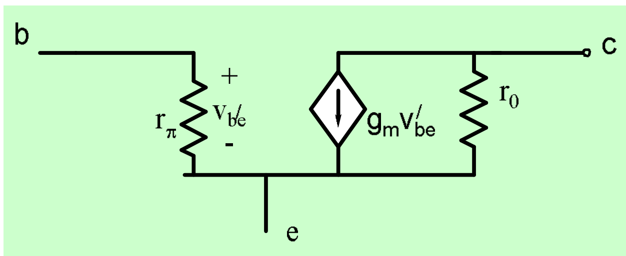


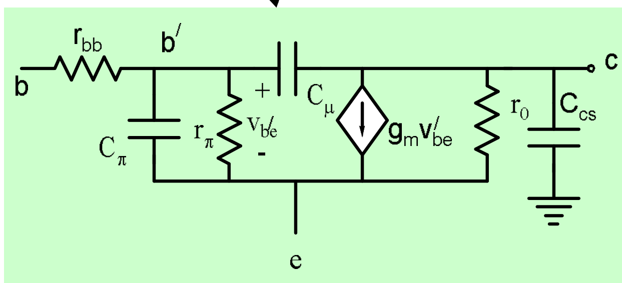
Low frequency behavior is caused by external capacitances

Mid-frequency region: all capacitances can be ignored

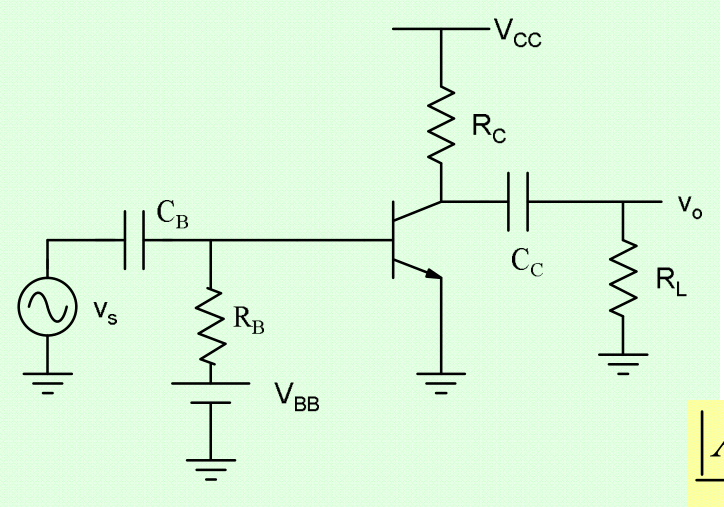
High frequency behavior is caused by internal transistor capacitances







Simple Common Emitter Amplifier



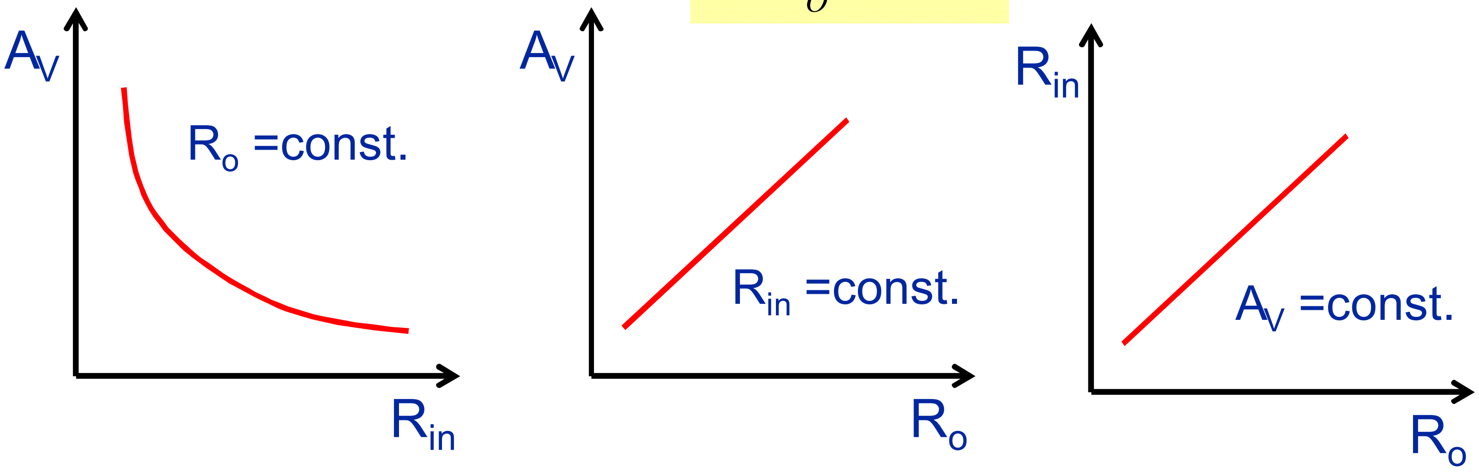
$$A_{VO} = -g_m R_C \Rightarrow \left|A_{VO}\right| = \frac{I_{CQ} R_C}{V_T}$$

$$R_{in} = R_B \| r_\pi \sim r_\pi = \frac{V_T}{I_{CQ}} \beta$$

$$v_{om} = Min\left\{V_{CEQ} - V_{CEsat}; \left(I_{CQ} \times R_C \| R_L\right) \times \left(\frac{HD_2}{25}\right)\right\}$$

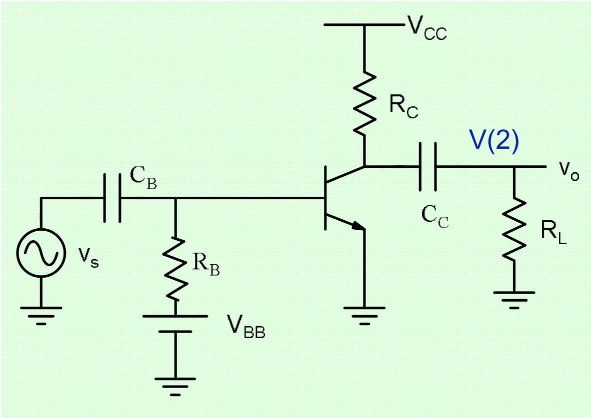
$$R_O = R_C \| r_o \sim R_C$$

$$\frac{\left|A_{VO}\right| \times R_{in}}{R_O} \leq \beta$$

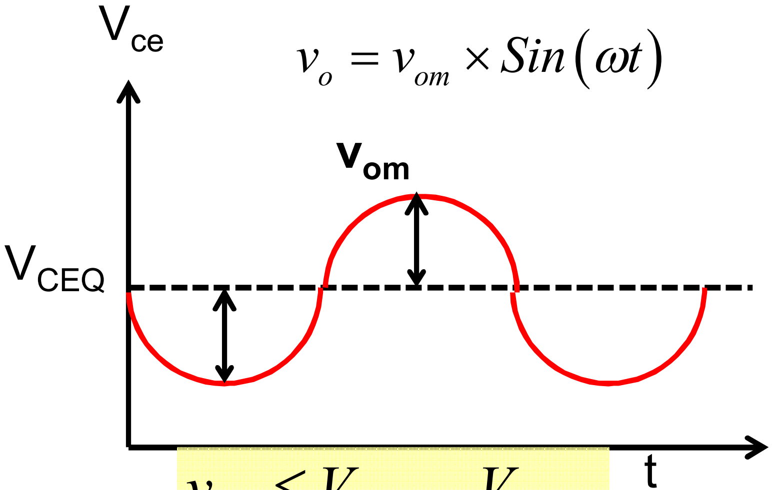


The performance of the BJT voltage amplifier is ultimately limited by β.

Output Voltage Swing



$$v_o = v_{om} \times Sin(\omega t)$$

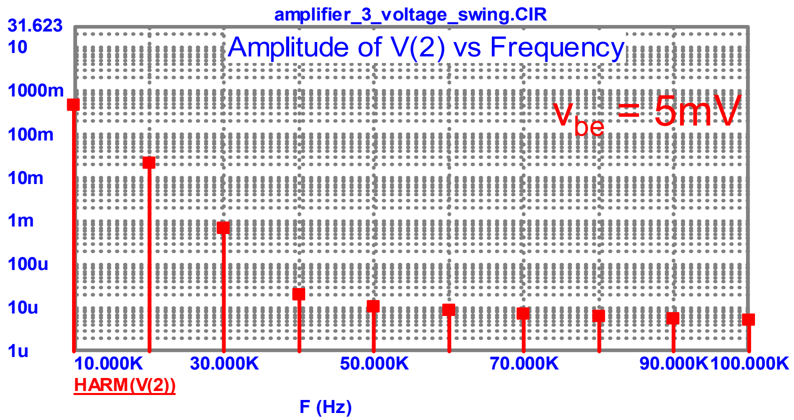


$$v_{om} \le V_{CEQ} - V_{CEsat}$$

$$\frac{v_{beo}}{V_T} = m$$

$$\frac{i_c}{I_{CQ}} = m \times Sin(\omega t) + \frac{(m \times Sin(\omega t))^2}{2} + \dots\dots\dots\dots$$

$$\frac{i_c}{I_{CQ}} = m \times Sin(\omega t) - \frac{m^2}{4} Cos(2\omega t) + \dots\dots$$

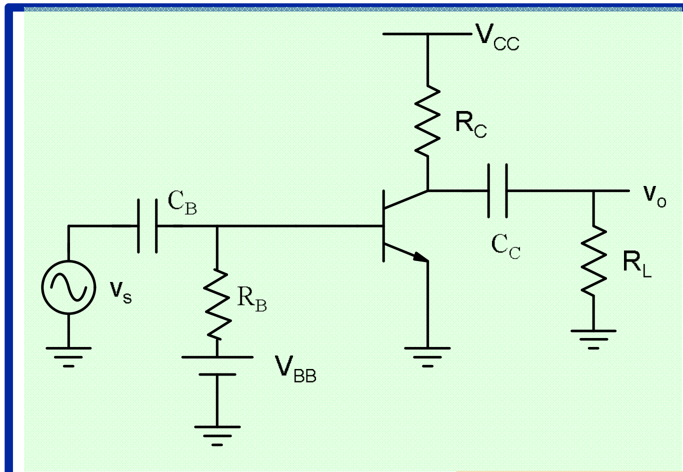


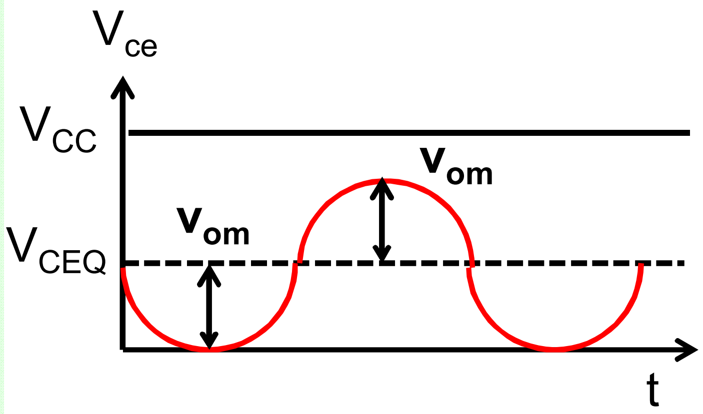
$$HD_2(\%) = \frac{v_{beo}}{V_T} \times 25$$

$$V_{om} \le \left(I_{CQ} \times R_C \| R_L\right) \times \left(\frac{HD_2}{25}\right)$$

$$v_{om} = Min\left\{V_{CEQ} - V_{CEsat} ; \left(I_{CQ} \times R_C \| R_L\right) \times \left(\frac{HD_2}{25}\right)\right\}$$

Design For Maximum Output Voltage Swing



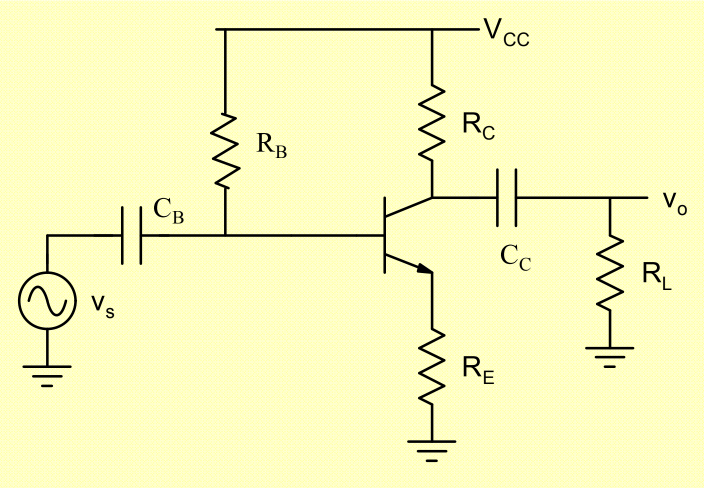


$$v_{om} = Min\left\{V_{CEQ} - V_{CEsat}; \left(I_{CQ} \times R_C \| R_L\right) \times \left(\frac{HD_2}{25}\right)\right\}$$

$$v_{om} \cong V_{CEQ} \cong \frac{V_{CC}}{1 + \left(1 + \frac{R_C}{R_L}\right)\frac{25}{HD_2(\%)}}$$

$$\text{Special Case: } V_{CEQ} \sim \frac{V_{CC}}{2} \sim v_{om}$$

CE Amplifier With Emitter Resistance



$$A_{VO} \cong -\frac{g_m R_C}{1 + g_m R_E} \qquad R_O \sim R_C$$

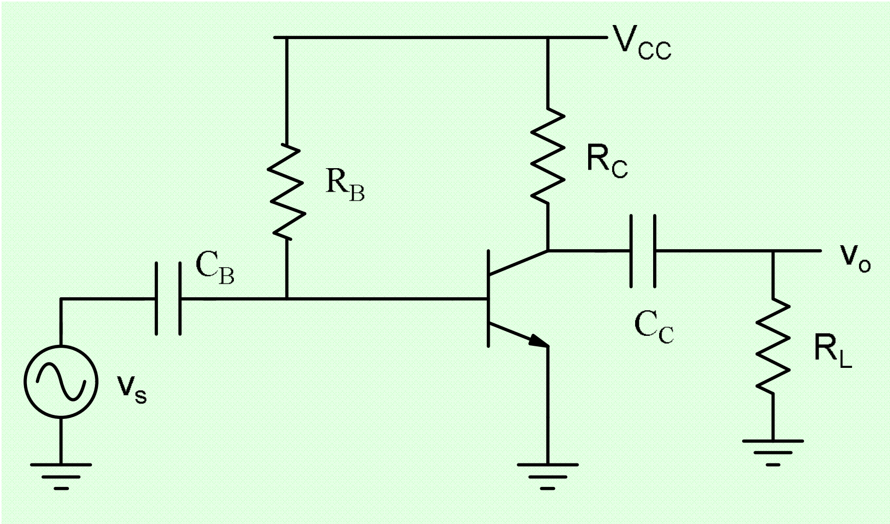
$$R_{in} = R_B \| (r_\pi + (1+\beta) R_E)$$

$$v_S = v_{be} \times \left(1 + g_m R_E\right)$$

Emitter Resistance results in negative feedback which improves linearity and reduces distortion

If disrortion is sufficiently reduced then $V_{CEQ} \sim \frac{V_{CC}}{2}$ is a good bias point for maximum output swing

Stability of Bias Point



$$S_\beta = \frac{\Delta I_{CQ}/I_{CQ}}{\Delta\beta/\beta} = 1$$

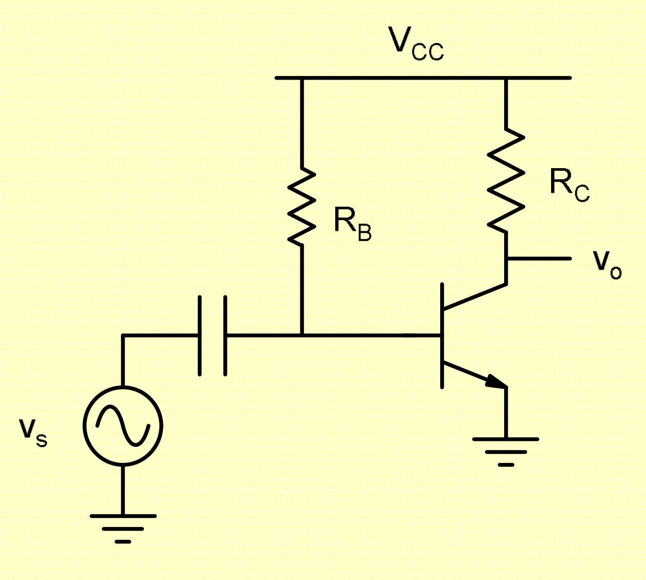
$$\text{Bias Point : } \mathrm{I}_{CQ}, V_{CEQ}$$

$$R_{in} \sim r_\pi = \frac{V_T}{I_{CQ}}\beta$$

$$\left|A_{VO}\right| = \frac{V_{CC} - V_{CEQ}}{V_T}$$

$$v_{om} = Min\left\{V_{CEQ} - V_{CEsat}; \left(I_{CQ} \times R_C \| R_L\right) \times \left(\frac{HD_2}{25}\right)\right\}$$

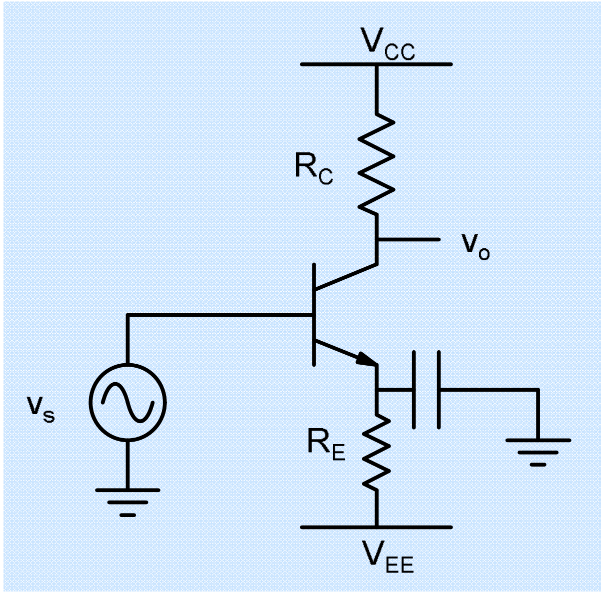
Stable Biasing with dual Supply Voltage



$$I_{CQ} = \beta \times I_{BQ}$$

$$I_{BQ} = \frac{V_{CC} - 0.7}{R_B}$$

$$S_\beta = \frac{\Delta I_{CQ} / I_{CQ}}{\Delta \beta / \beta} = 1$$

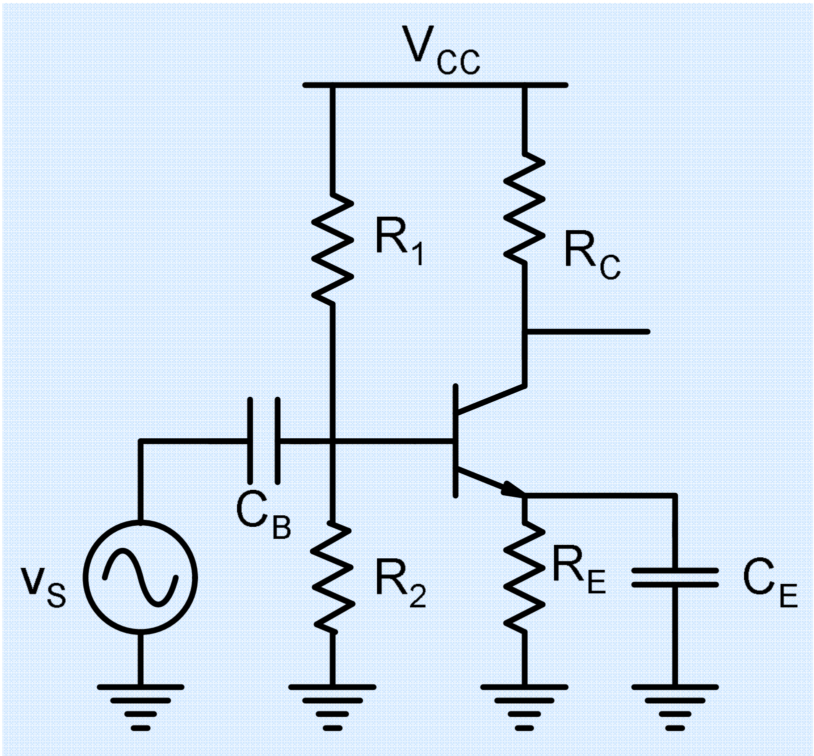


$$I_{CQ} = \left(\frac{\beta}{\beta + 1} \right) I_{EQ}$$

$$I_{EQ} = \frac{-0.7 - V_{EE}}{R_E}$$

$$S_\beta << 1$$

Stable Biasing with Single Supply Voltage



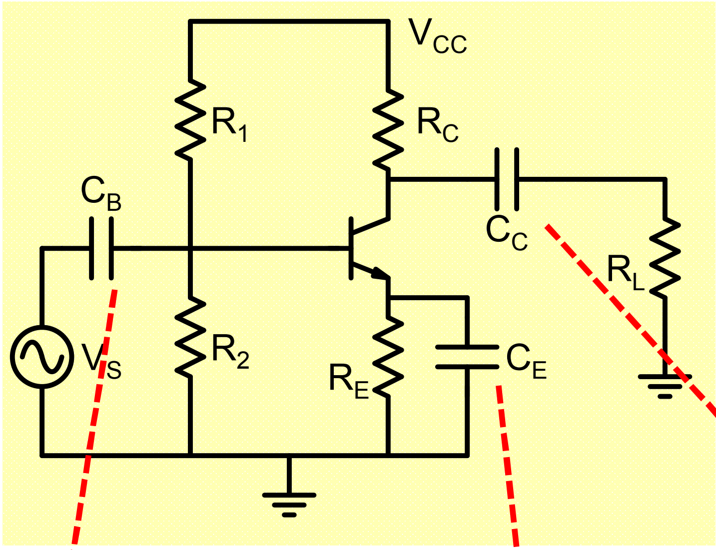
$$I_C = \frac{V_{BB} - V_{BE}}{\frac{R_B}{\beta} + R_E}$$

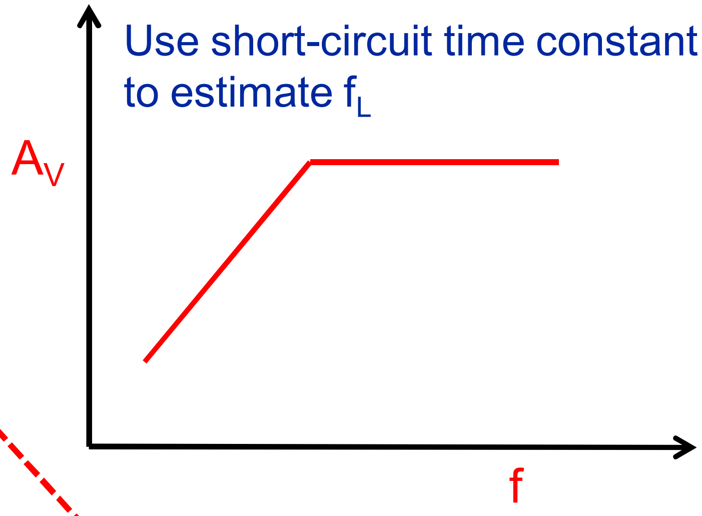
$$S = \frac{\Delta I_C / I_C}{\Delta\beta/\beta} = \frac{1}{1 + \frac{R_E\beta}{R_B}}$$

$$R_E >> \frac{R_B}{\beta}$$

$$y = \frac{I_{C2} - I_{C1}}{I_{C1}} = \frac{(\beta_2 - \beta_1)x}{\beta_1 \times (x + \beta_2)}; x = \frac{R_B}{R_E} \qquad x = \frac{R_B}{R_E} \le \frac{y\beta_2\beta_1}{\beta_2 - \beta_1 \times (1+y)}$$

Lower Cutoff Frequency





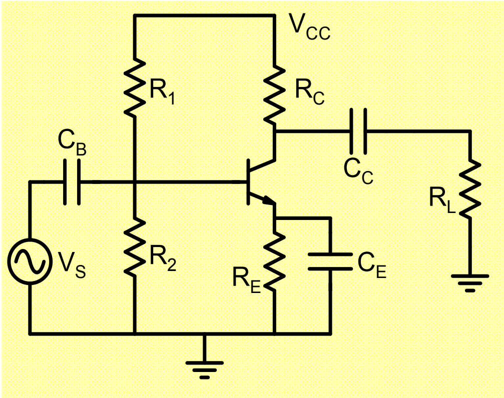
$$f_B = \frac{1}{2\pi C_B \times (R_S + R_B \| r_\pi)}$$

$$f_C = \frac{1}{2\pi C_c \times (R_C + R_L)}$$

$$f_E = \frac{1}{2\pi C_E \times \left(R_E \left\| \frac{(R_S \| R_B) + r_\pi}{\beta}\right.\right)}$$

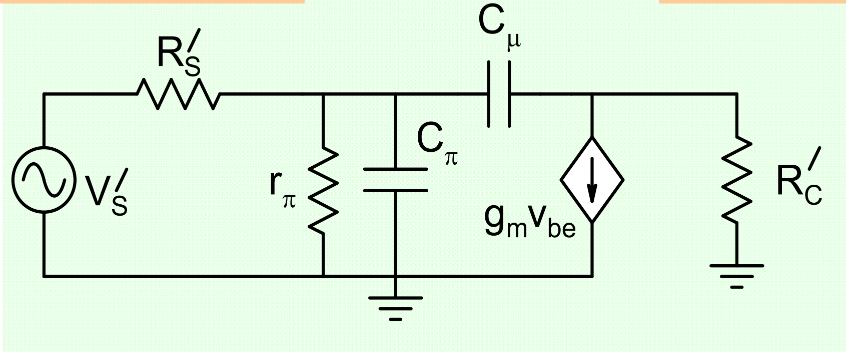
If one of the 3dB frequencies is much larger compared to others,we take this frequency as the 3dB frequency of the circuit. Usually it is f_E

Upper Cutoff Frequency

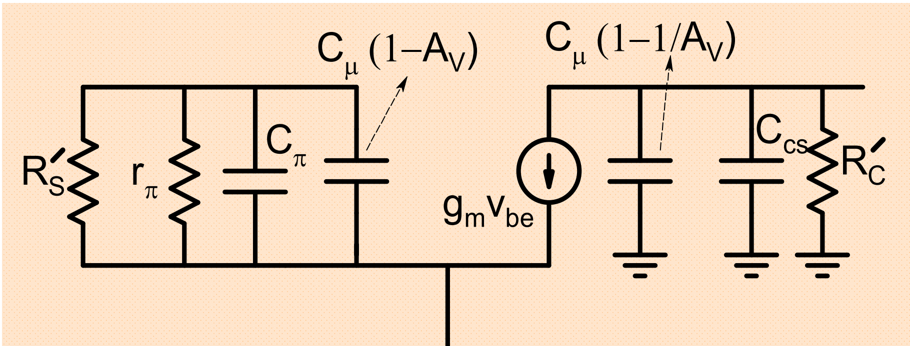


$R_S' = (R_S \| R_B) + r_{bb}$

$R_C' = R_C \| R_L$



Method: Open circuit time constant.
Apply Miller's theorem to simplify

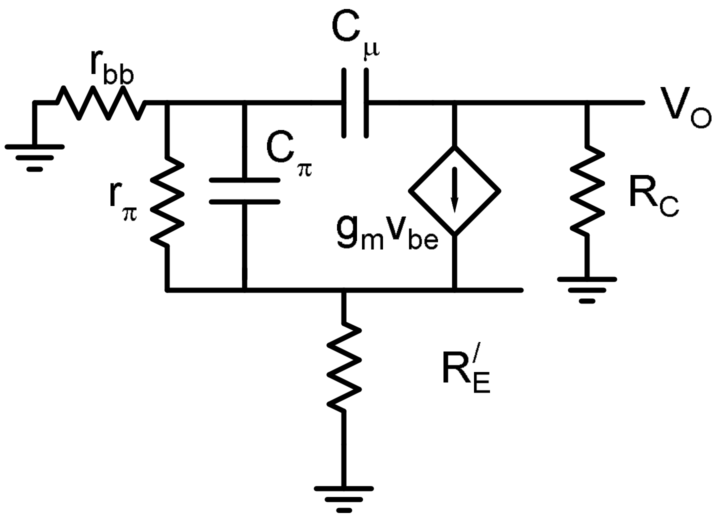


$A_V \cong -g_m R_C'$

$$\omega_H \cong \frac{1}{(R_S' \| r_\pi)\{C_\pi + C_\mu(1 + g_m R_C')\} + R_C' C_\mu}$$

Upper Cutoff Frequency

Open circuit time constant : General expressions



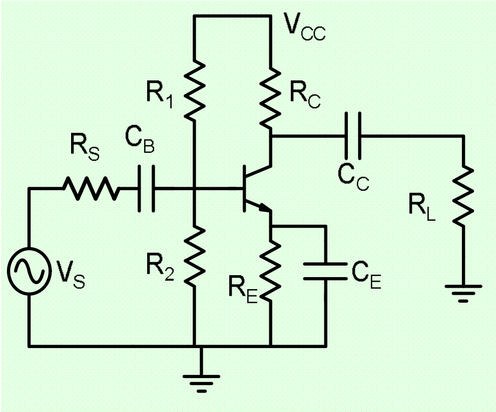
$$R_\pi = \left(1 + \frac{R'_E}{r_{bb}}\right)\left(r_\pi \,\middle\|\, \frac{r_{bb}}{1 + g_m R'_E}\right)$$

$$R_\mu = r_{bb}(1 - x) + R_C \times (1 + x\beta)$$

$$x = \frac{r_{bb}}{r_{bb} + r_\pi + \beta R'_E}$$

$$f_H \cong \frac{1}{2\pi \times \left(R_\pi C_\pi + R_\mu C_\mu\right)}$$

Design Perspective

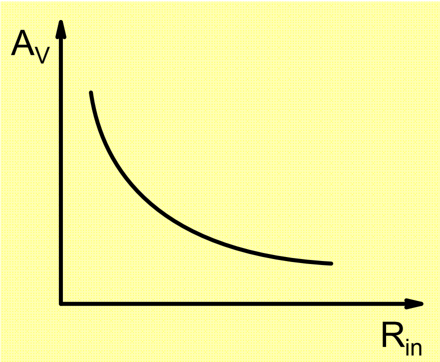


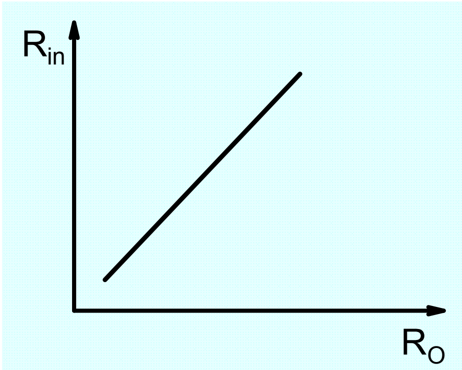
$$A_V = -\frac{I_{CQ}}{V_T} \times R_C \| R_L$$

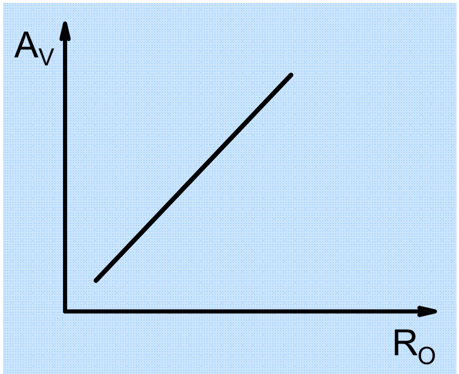
$$R_{in} = r_\pi \| R_B$$

$$R_o = R_C$$

Tradeoff between Voltage Gain, Input Resistance and Output Resistance



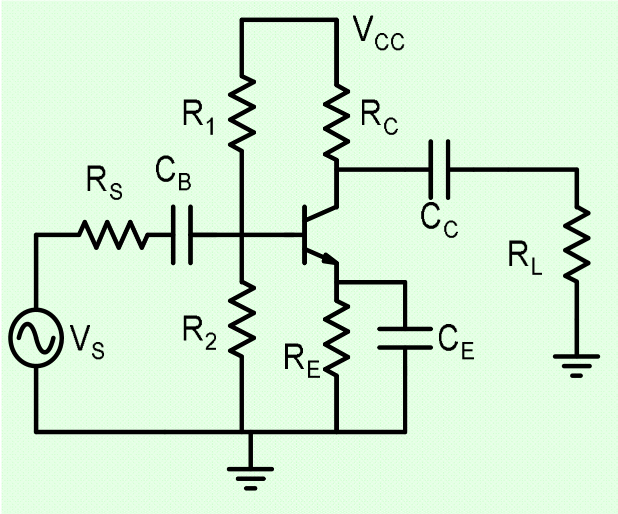


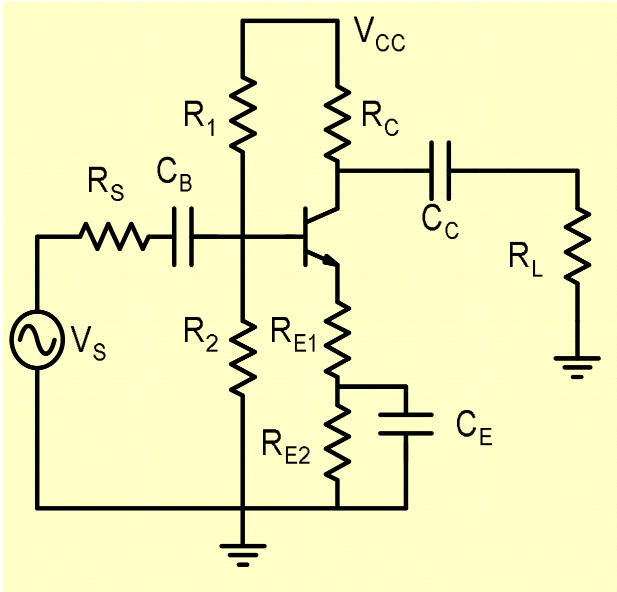


$$\frac{A_V \times R_{in}}{R_O} = \beta \times \frac{1}{1 + \frac{R_o}{R_L}} \times \frac{1}{1 + \frac{r_\pi}{R_B}}$$

$$\frac{A_V \times R_{in}}{R_O} \leq \beta$$

Gain-Input resistance Tradeoff





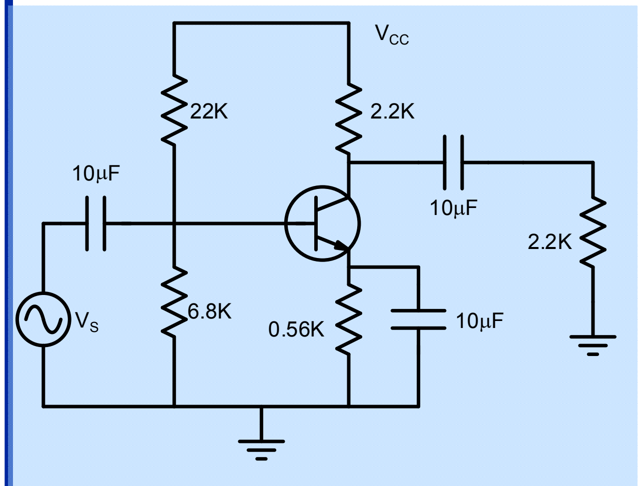
$$A_V = -g_m \times R_C \| R_L$$

$$A_V = -\frac{g_m}{1 + g_m R_{E1}} \times R_C \| R_L$$

$$R_{in} = r_\pi \| R_B$$

$$R_{in} = r_\pi \times \left(1 + g_m R_{E1}\right) \| R_B$$

Gain-Swing Tradeoff



$$A_V = -\frac{I_{CQ}}{V_T} \times R_C \| R_L$$

$$V_{om} = Min.\left\{ (V_{CEQ} - V_{CEsat.}), \frac{H_{D2}}{25} \times I_{CQ} R_C \| R_L \right\}$$

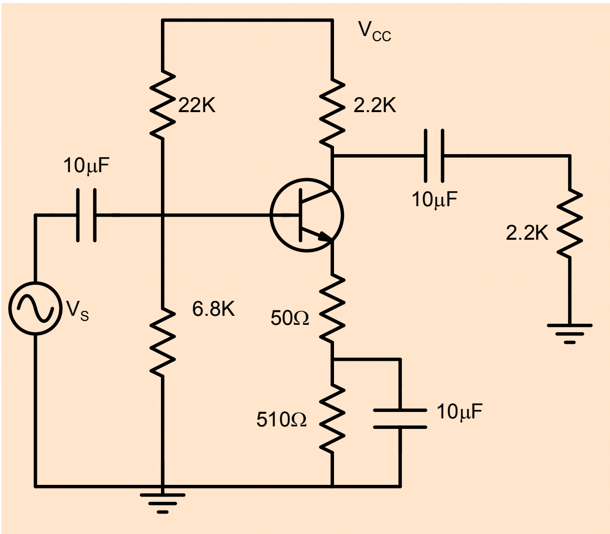
$\beta = 100; V_{CC} = 12V$

$I_{CQ} = 3.4mA; V_{CEQ} = 2.57V$

$A_V = 110.7; R_{in} = 0.82K\ ; R_O = 2.2K$

$v_{om} = 0.39V\ @\ THD = 1.9\%$

$f_L = 1.67kHz; f_H = 5.8MHz$



$\beta = 100$

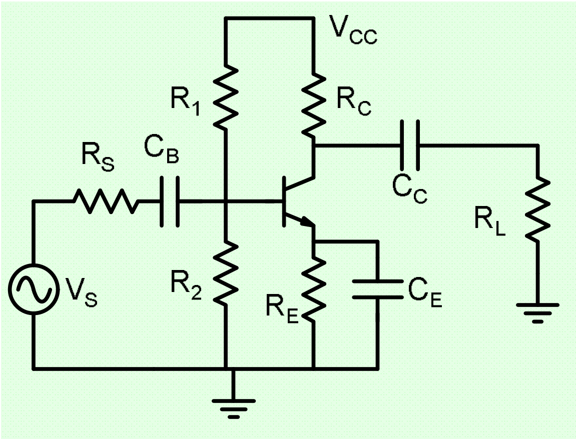
$I_{CQ} = 3.4mA; V_{CEQ} = 2.57V$

$A_V = 18.2; R_{in} = 2.76K\ ; R_O = 2.2K$

$v_{om} = 2V\ @\ THD = 1.8\%$

$f_L = 0.3kHz; f_H = 26.46MHz$

Gain-Bandwidth Tradeoff



$$\omega_L = \frac{1}{C_E \times \left(R_E \left\| \frac{(R_S \| R_B) + r_\pi}{\beta}\right.\right)} \cong \frac{\beta}{C_E \times r_\pi}$$

$$\omega_L \times R_{in} = \frac{\beta}{C_E}$$

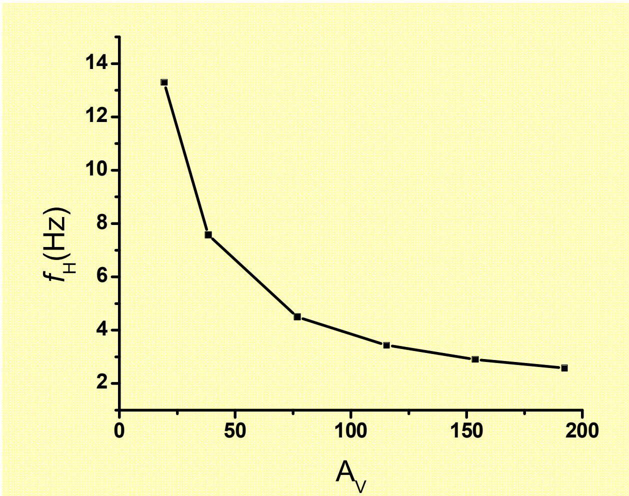
$$\frac{A_V \times R_{in}}{R_O} \le \beta$$

$$\frac{A_V}{R_O \times \omega_L} \le C_E$$

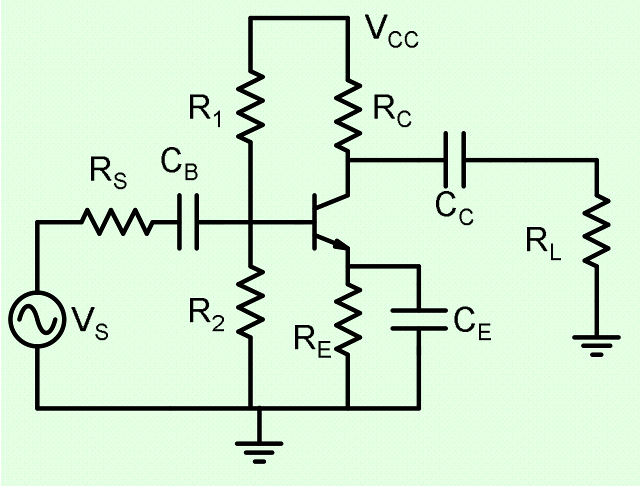
Upper Cutoff Frequency

$$\omega_H \cong \frac{1}{(R'_S \| r_\pi)\{C_\pi + C_\mu(1 + g_m R'_C)\} + R'_C C_\mu}$$

$$A_V \cong -g_m R'_C$$



Design of CE Amplifier



Specifications:

$A_V \geq 100 \pm 20\%$ at T=300k

$R_O \leq 2.2k$

$R_{in} \geq 0.75k$

$v_{om} \geq 0.35V$ with THD $\leq 2\%$

$f_L \leq 2$ kHz

$f_H \geq 5$MHz

$R_L = 2.2k; R_S \sim 50\Omega$

Constraints : $V_{CC} \leq 9V$; Low cost; Low power

Design variables:

R_1, R_2, R_C, R_E

C_B, C_C, C_E

V_{CC}

Transistor

Design variables:

$\left\{\text{Bias point: } I_{CQ}, V_{CEQ}, V_E\right\}$

R_C

C_E

Transistor $\left\{\beta, \tau_F, C_{jeo}, C_{jco}\right\}$

$$I_{CQ} = \frac{V_{CC}\dfrac{R_2}{R_1+R_2} - V_{BE}(on)}{\dfrac{R_B}{\beta} + R_E}; R_B = \frac{R_1R_2}{R_1+R_2}$$

$$S = \frac{\Delta I_{CQ}/I_{CQ}}{\Delta\beta/\beta} = \frac{1}{1+\dfrac{\beta R_E}{R_B}}; \quad x_b = \frac{R_B}{r_\pi}$$

$$V_{CC} = V_{CEQ} + I_{CQ}(R_C + R_E)$$

$$A_V = -\frac{I_{CQ}}{V_T} \times R_C \| R_L$$

$$R_{in} = r_\pi \| R_B$$

$$R_o = R_C$$

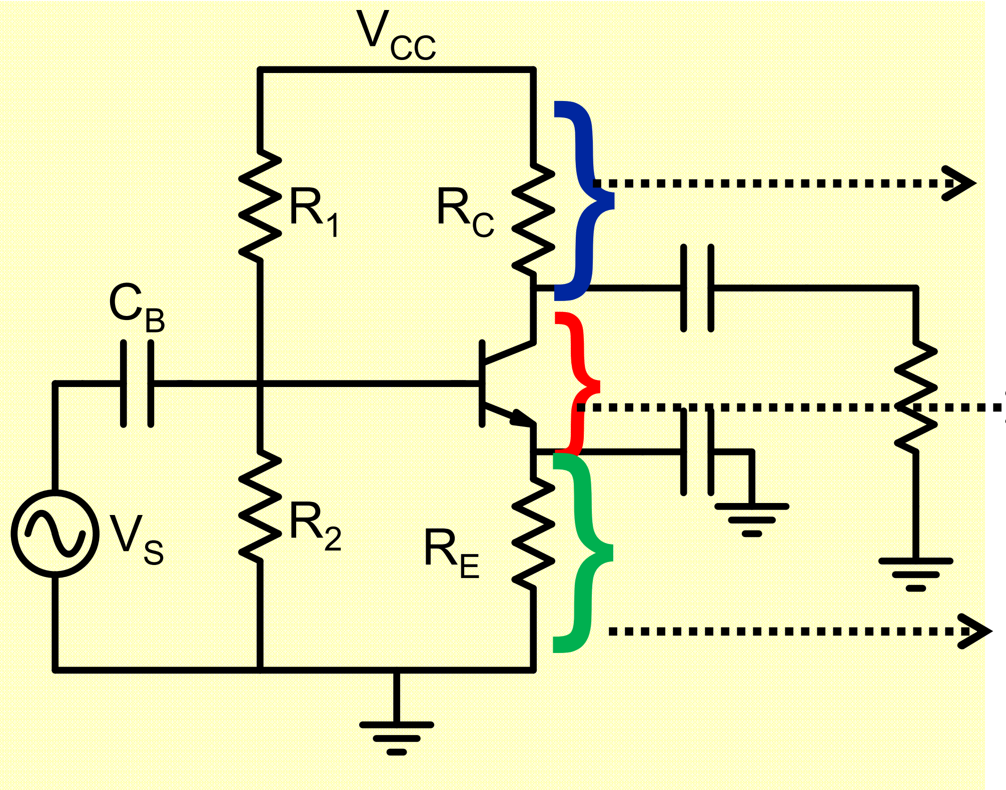
$$\omega_L = \frac{1}{C_E \times \left(R_E \left\| \dfrac{(R_S \| R_B) + r_\pi}{\beta}\right.\right)}$$

$$V_{om} = Min.\left\{(V_{CEQ} - V_{CEsat.}), \frac{H_{D2}}{25} \times I_{CQ}R_C \| R_L\right\}$$

$$\omega_H \cong \frac{1}{\left((R_S \| R_B) + r_{bb}\right) \| r_\pi \{C_\pi + C_\mu(1 + g_m R_C \| R_L)\} + C_\mu R_C \| R_L}$$

G-Number

Design of CE Amplifier



$$I_{CQ} \times R_C \| R_L = A_V \times V_T$$

$$I_{CQ} \times R_C \| R_L \geq v_{om} \times \frac{25}{HD_2}$$

$$V_{CEQ} \geq v_{om} + 0.2$$

$$V_E = \frac{x_b}{x} \times V_T \times \beta$$

$$x = \frac{R_B}{R_E} \leq \frac{y\beta_2\beta_1}{\beta_2 - \beta_1 \times (1+y)}; y = \frac{I_{C2} - I_{C1}}{I_{C1}}; x_b = \frac{R_B}{r_\pi}$$

CE Amplifier : Problems and Solutions