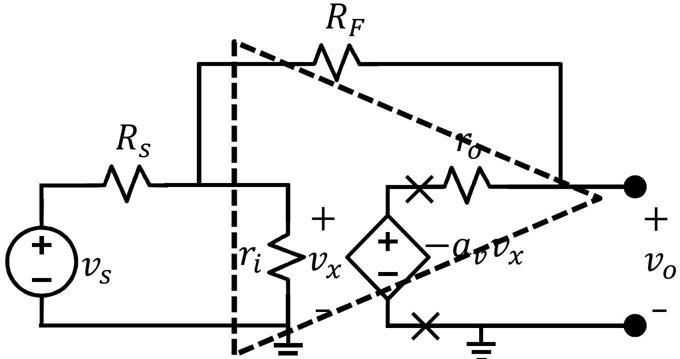
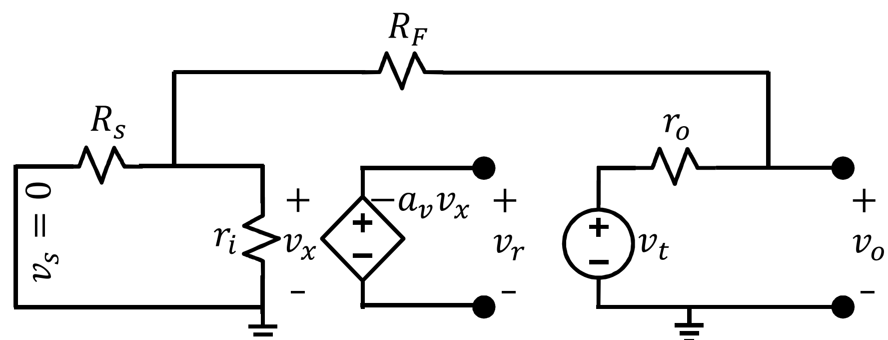
Return Ratio!

1. [illegible]
2. [illegible]
3. [illegible]
4. [illegible]
5. [illegible]

1. Set all independent sources to zero
2. Break the feedback loop by disconnecting a dependent source
3. Call signal right after dependent source: s_t
4. Call the return signal by dependent source: s_r

Define return ratio of that dependent source as $\mathcal{R} = -s_r/s_t$



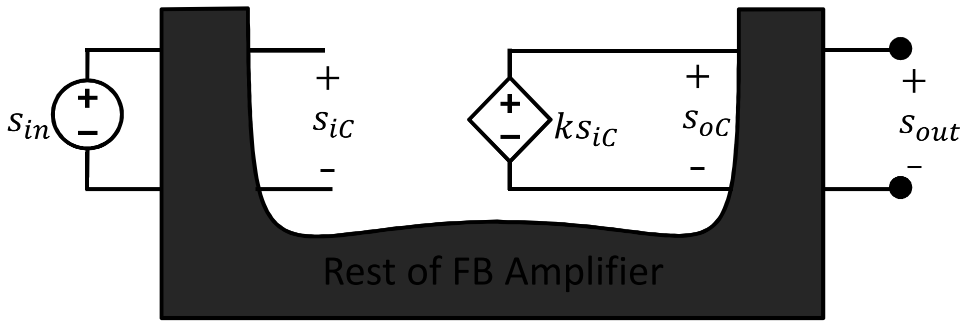


$$v_x = \frac{r_i \parallel R_s}{r_i \parallel R_s + R_F + r_o} v_t \qquad v_r = -a_v v_x$$

$$\mathcal{R} = -\frac{v_r}{v_t} = a_v \frac{r_i \parallel R_s}{r_i \parallel R_s + R_F + r_o}$$

Return Ratio!

1.
2.
3.
4.
5.



$$s_{iC} = \frac{B_1}{1 + kH} s_{in}$$

$$A = \frac{s_{out}}{s_{in}} = \frac{kB_1B_2}{1 + kH} + d$$

$$s_{in} = 0 \quad \rightarrow s_{iC} = -Hs_t \quad \rightarrow \mathcal{R} = kH$$

$$A = \frac{s_{out}}{s_{in}} = \frac{g}{1 + \mathcal{R}} + d = \frac{\mathcal{R}(\frac{g}{\mathcal{R}} + d)}{1 + \mathcal{R}} + \frac{d}{1 + \mathcal{R}}$$

$$A_\infty = \frac{g}{\mathcal{R}} + d \qquad A = \frac{\mathcal{R}}{1 + \mathcal{R}} A_\infty + \frac{d}{1 + \mathcal{R}}$$

$$s_{oC} = ks_{iC}$$

$$s_{iC} = B_1 s_{in} - H s_{oC}$$

$$s_{out} = ds_{in} + B_2 s_{oC}$$

$$B_1 = \left.\frac{s_{iC}}{s_{in}}\right|_{s_{oC}=0} = \left.\frac{s_{iC}}{s_{in}}\right|_{k=0}$$

$$B_2 = \left.\frac{s_{out}}{s_{oC}}\right|_{s_{in}=0}$$

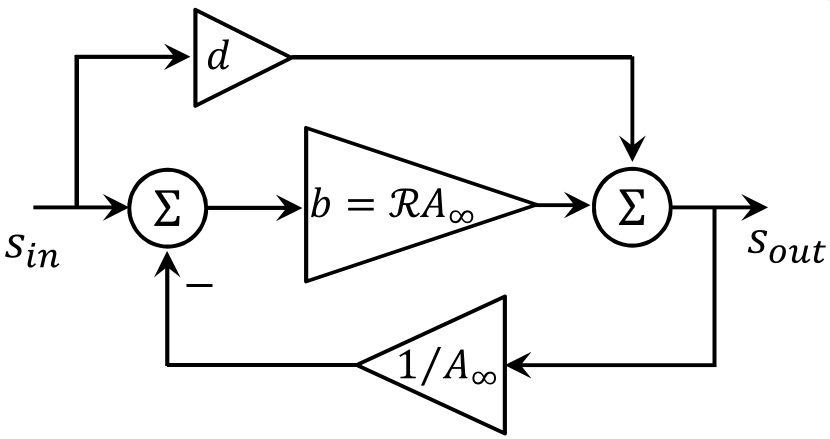
$$H = -\left.\frac{s_{iC}}{s_{oC}}\right|_{s_{in}=0}$$

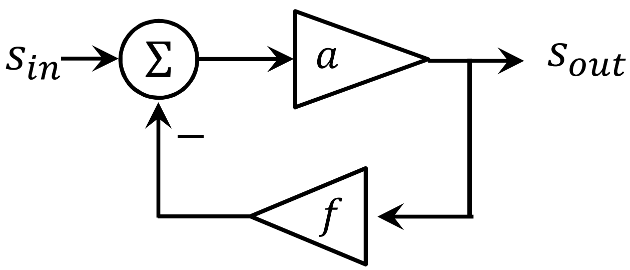
$$d = \left.\frac{s_{out}}{s_{in}}\right|_{s_{oC}=0} = \left.\frac{s_{out}}{s_{in}}\right|_{k=0}$$

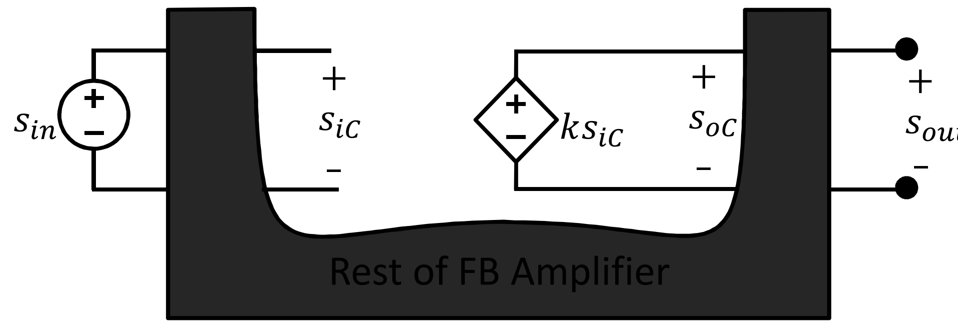
Return Ratio!

1.
2.
3.
4.
5.

$$A = \frac{\mathcal{R}}{1+\mathcal{R}} A_\infty + \frac{d}{1+\mathcal{R}}$$







Return Ratio!

1.
2.
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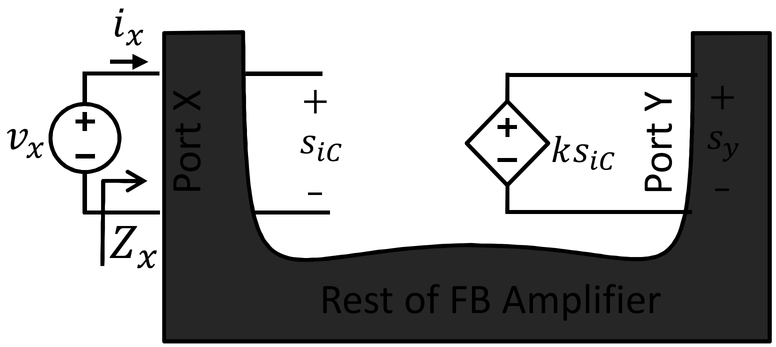

Linear circuit

$$v_x = a_1 i_x + a_2 s_y$$

$$s_{iC} = a_3 i_x + a_4 s_y$$

$$Z_{port}\Big|_{k=0} = \frac{v_x}{i_x}\Big|_{k=0} = \frac{v_x}{i_x}\Big|_{s_y=0} = a_1$$

$$s_y = ks_{iC}$$

$$Z_{port} = \frac{v_x}{i_x} = a_1 \frac{1 - k\left(a_4 - \frac{a_2 a_3}{a_1}\right)}{1 - ka_4}$$

Port Open: $i_x = 0$ $\quad s_{iC} = a_4 s_y$ $\quad s_r = ks_{iC}$

$$\mathcal{R}(\text{open}) = -\frac{s_r}{s_t} = -ka_4$$

Port Short: $v_x = 0$ $\quad i_x = -\frac{a_2}{a_1} s_y$ $\quad s_y = s_t$

$$s_{iC} = (a_4 - \frac{a_2 a_3}{a_1}) s_t \qquad s_r = ks_{iC}$$

$$\mathcal{R}(\text{short}) = -\frac{s_r}{s_t} = -k\left(a_4 - \frac{a_2 a_3}{a_1}\right)$$

$$Z_{port} = Z_{port}\Big|_{k=0} \frac{1 + \mathcal{R}(\text{short})}{1 + \mathcal{R}(\text{open})}$$

Blackman's impedance formula

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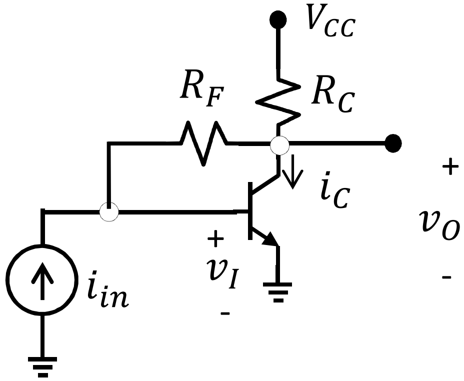

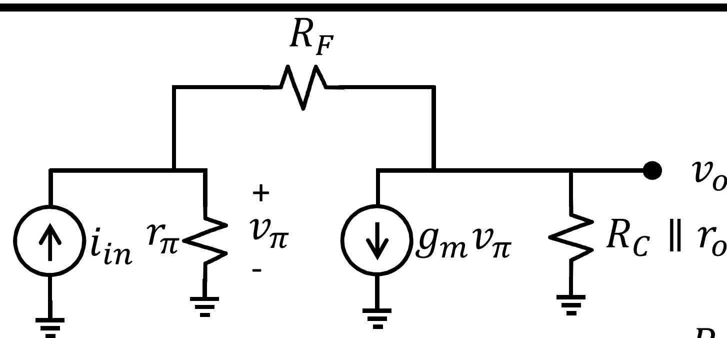

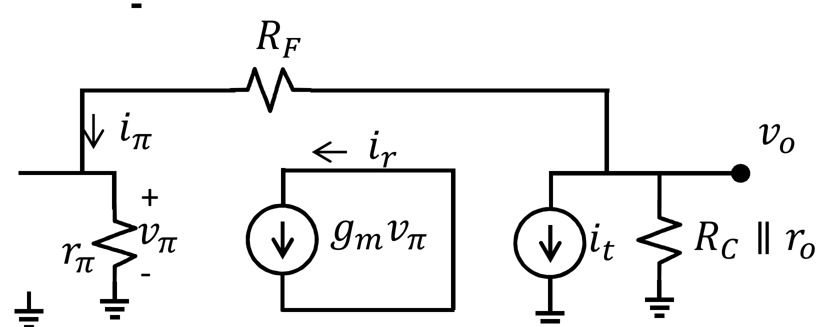

$$A_\infty = \left.\frac{v_o}{i_{in}}\right|_{g_m=\infty} = -R_F$$

$$d = \left.\frac{v_o}{i_{in}}\right|_{g_m=0} = [r_\pi \parallel (R_F + R_C \parallel r_o)] \frac{R_C \parallel r_o}{R_F + R_C \parallel r_o}$$

$$i_\pi = -\frac{R_C \parallel r_o}{r_\pi + R_F + R_C \parallel r_o} i_t \qquad i_r = g_m r_\pi i_t \qquad \mathcal{R} = -\frac{i_r}{i_t} = \frac{g_m r_\pi (R_C \parallel r_o)}{r_\pi + R_F + R_C \parallel r_o}$$

$$A = \frac{\mathcal{R}}{1+\mathcal{R}} A_\infty + \frac{d}{1+\mathcal{R}}$$

$$R_{out} = \left.Z_{out}\right|_{g_m=0} \frac{1+\mathcal{R}(\text{short})}{1+\mathcal{R}(\text{open})}$$

$$= [(r_\pi + R_F) \parallel R_C \parallel r_o] \frac{1+0}{1+\mathcal{R}}$$

Session ?:
Principles of Electronics

Voltage Regulators

Voltage Regulators

1. [illegible]
2. [illegible]
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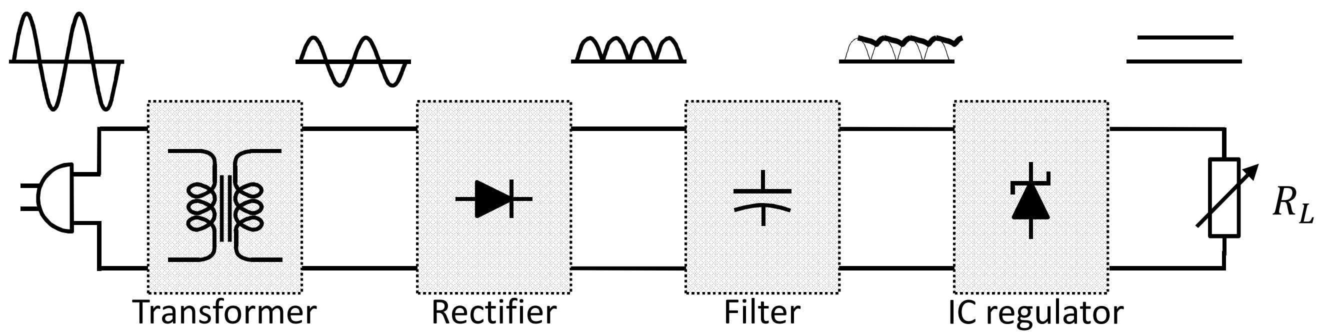
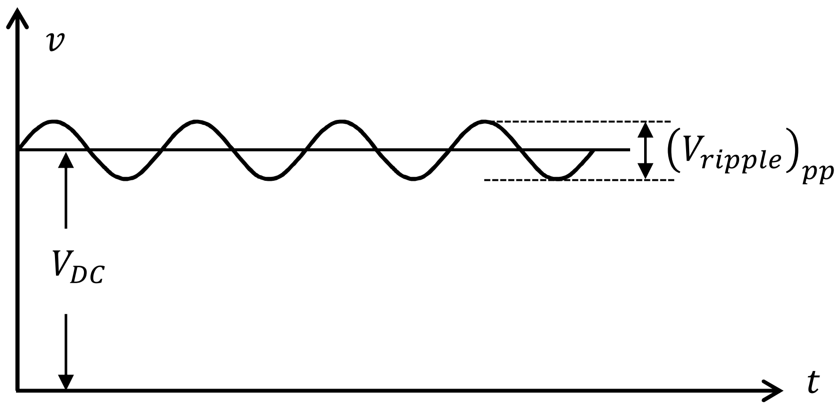
5. [illegible]

Power Supplies (Voltage Regulators)



Definitions



Ripple Voltage

$$r \equiv \frac{V_{r(rms)}}{V_{Dc}} \times 100\%$$

Voltage Regulation

$$\%V.R. \equiv \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100\%$$

Rectifier

1.
2.
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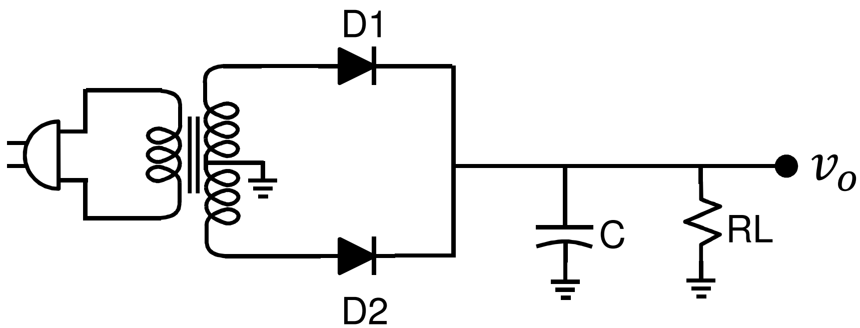
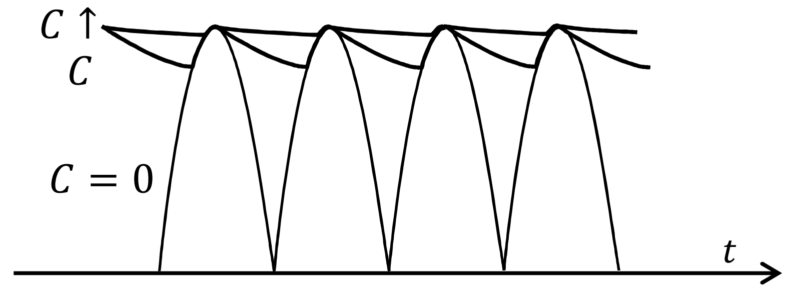
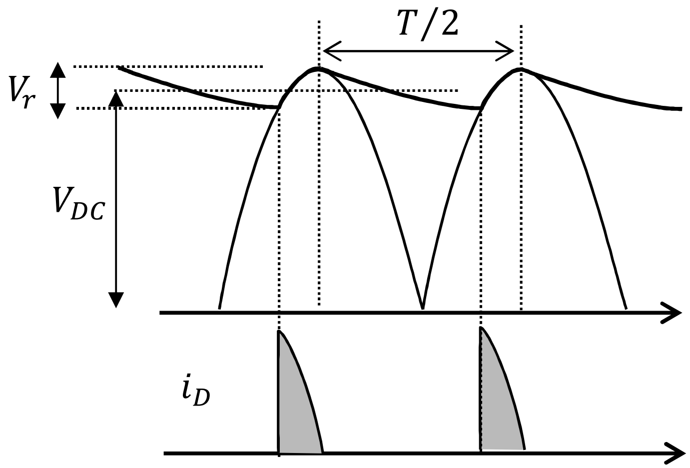
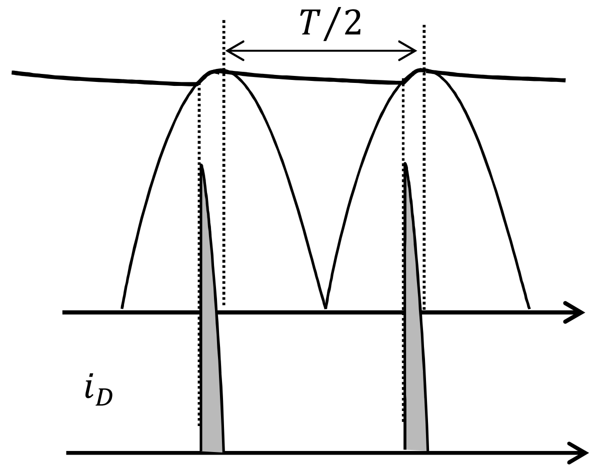






$$V_r = \frac{I_{DC}}{2fC}$$

$$V_{DC} = V_m - \frac{V_r}{2}$$



$$C \nearrow \;\Longrightarrow\; \begin{matrix} V_r \searrow \\ i_{D_{max}} \nearrow \end{matrix}$$

Zener Diode

1.
2.
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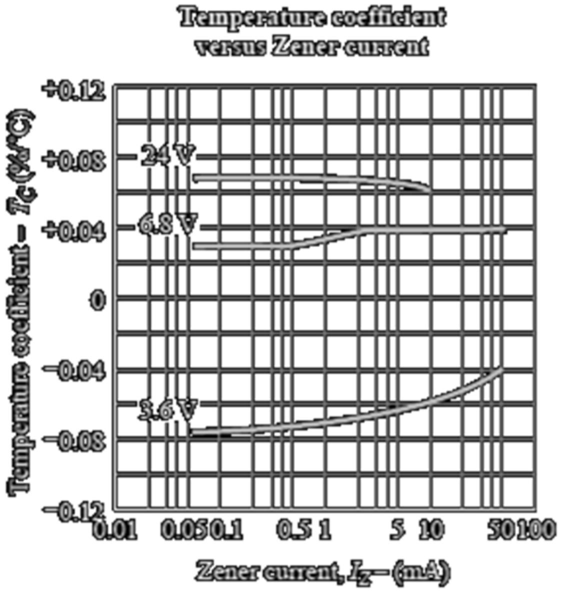
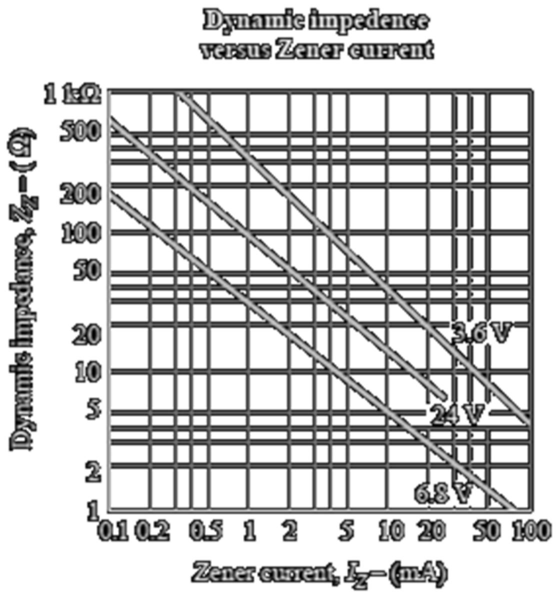
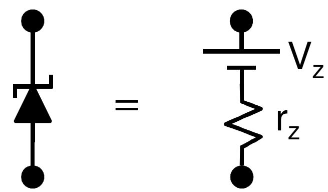
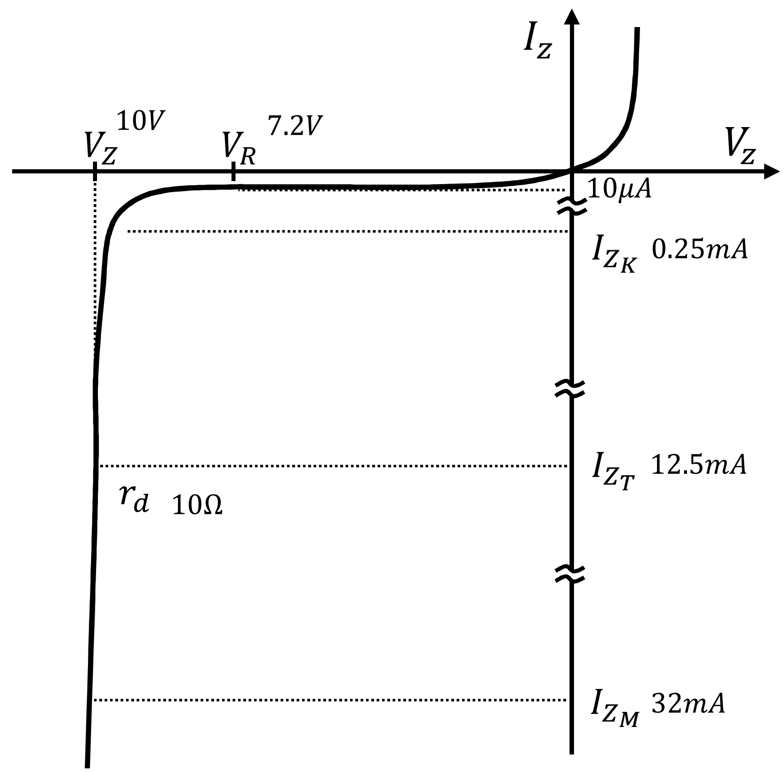






$$T_C = \frac{\Delta V_Z / V_Z}{T_1 - T_0} \times 100\%$$

$+0.072(\%/°C)$



Zener Diode Regulator

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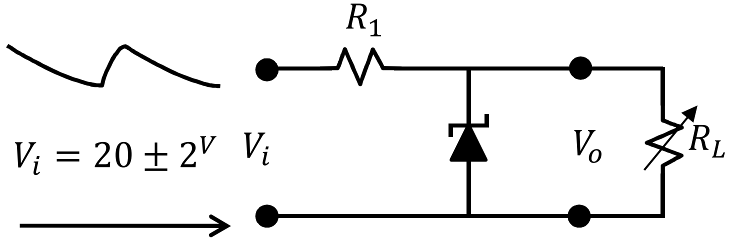
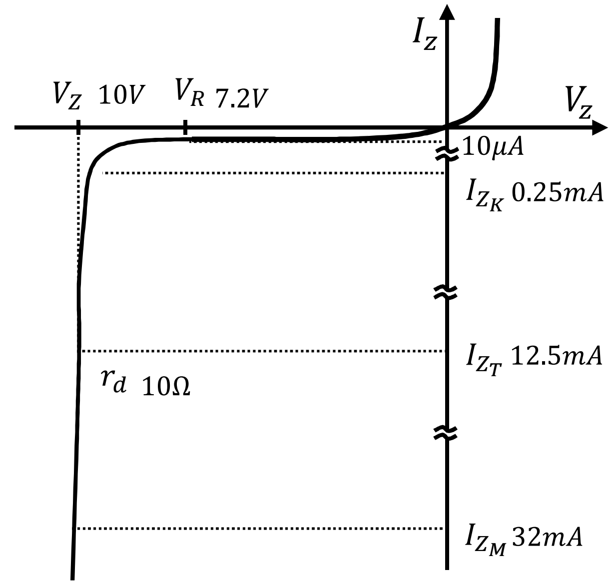
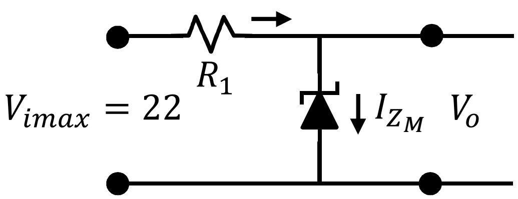


10 ± 0.05^V



1. Find R_1 such that circuits work for no load

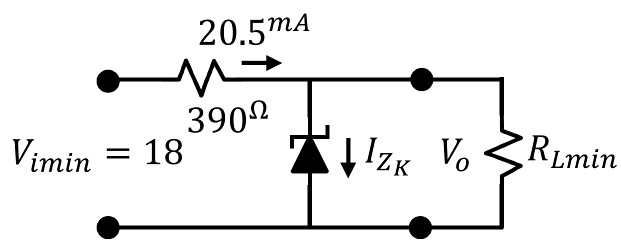


$$I_{Z_M} > \frac{22 - 10}{R_1}$$

$$R_1 > 375^{\Omega}$$

$$R_1 = 390^{\Omega}$$

2. Find R_{Lmin}



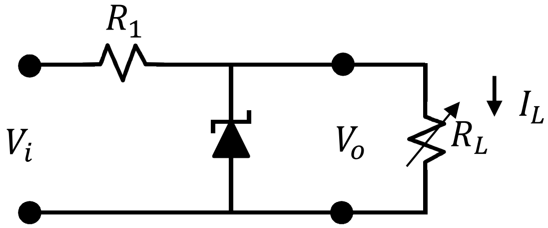
$$R_{Lmin} = \frac{10}{20.5 - 0.25} = 493^{\Omega}$$

3. Find output ripple

$$V_{o_r} = V_{i_r} \frac{r_d}{r_d + R_1} = 0.1^V$$

$$V_o = 10 \pm 0.05^V$$

Stability Measures



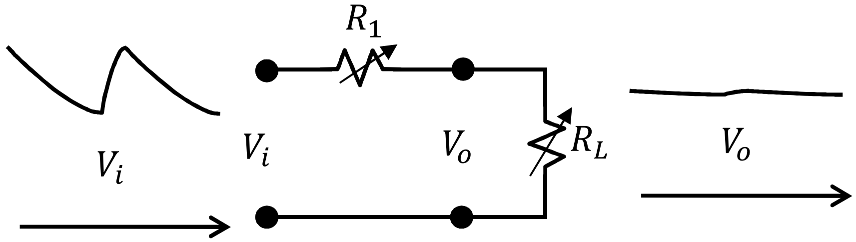
$$V_o = V_o(I_L, V_i, T)$$

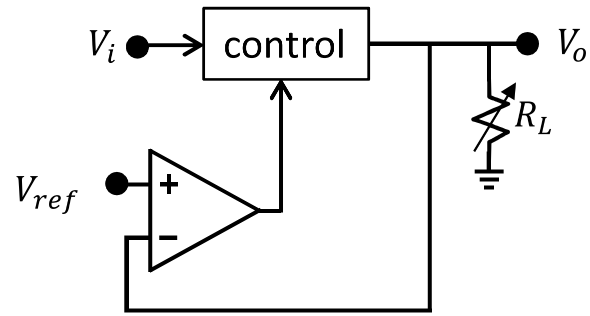
Stability measures

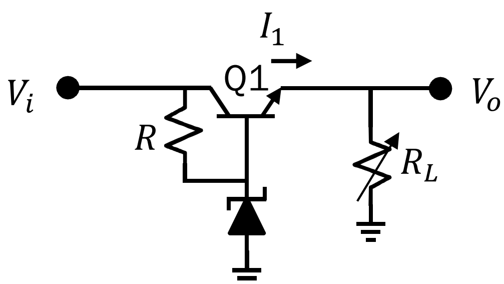
$$S_I = \left.\frac{\partial V_O}{\partial I_L}\right|_{\substack{V_i = cte \\ T = cte}} \qquad S_V = \left.\frac{\partial V_O}{\partial V_i}\right|_{\substack{I_L = cte \\ T = cte}} \qquad S_T = \left.\frac{\partial V_O}{\partial T_i}\right|_{\substack{I_L = cte \\ V_i = cte}}$$

Series Voltage Regulators

1.
2.
3.
4.
5.







⊖ feedback

$$V_o \searrow \Rightarrow V_{BE} \nearrow \Rightarrow I_1 \nearrow \Rightarrow V_o \nearrow$$

Series Voltage Regulators

1. □□□□□□□□
2. □□□□□□□□□□
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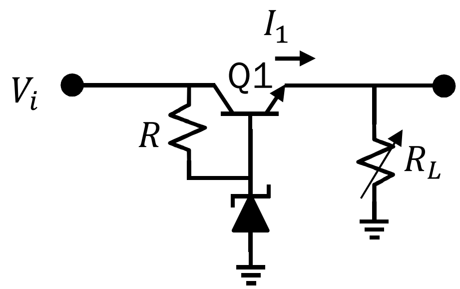
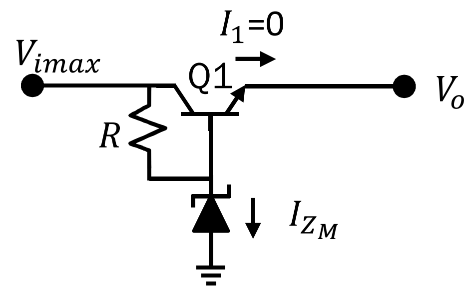
$V_i = 20 \pm 2^V$



1. Find R such that circuits work for no load

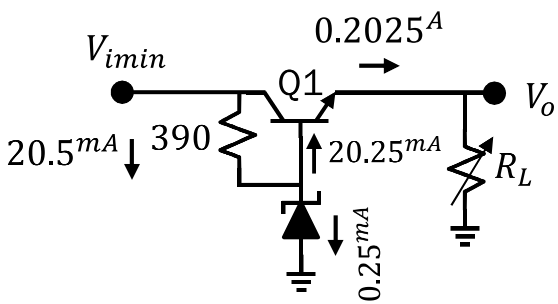


$$I_{Z_M} > \frac{22-10}{R}$$

$$R > 375^{\Omega}$$

$$R = 390^{\Omega}$$

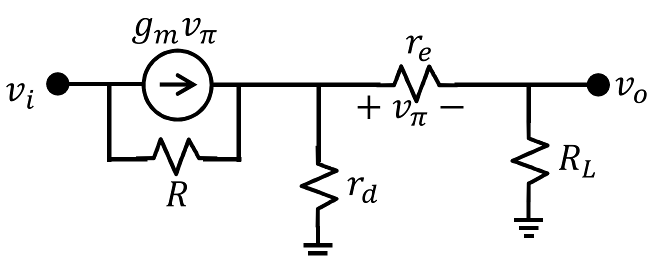
2. Find R_{Lmin}



$$R_{Lmin} = \frac{9.3}{0.2025} = 4.6^{\Omega}$$

3. Find output ripple

$R_L = 100^{\Omega}$, $I_C = 93^{mA}$, $r_m = 0.26^{\Omega}$



$$V_{o_r} = V_{i_r} \frac{r_d}{r_d + R} \frac{R_L}{R_L + r_m} \cong V_{i_r} \frac{r_d}{r_d + R} = 0.1$$

$$V_o = 9.3 \pm 0.05^V$$

Series Voltage Regulators

1. □□□□□□□□
2. □□□□□□□□□□
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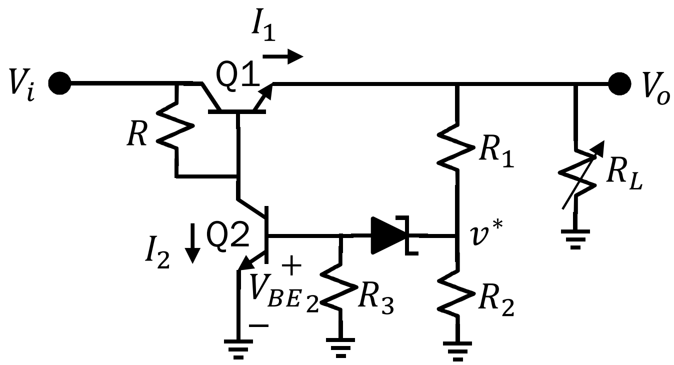
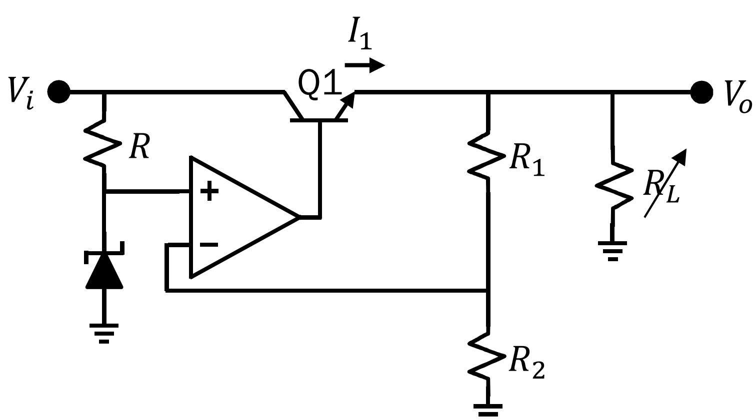


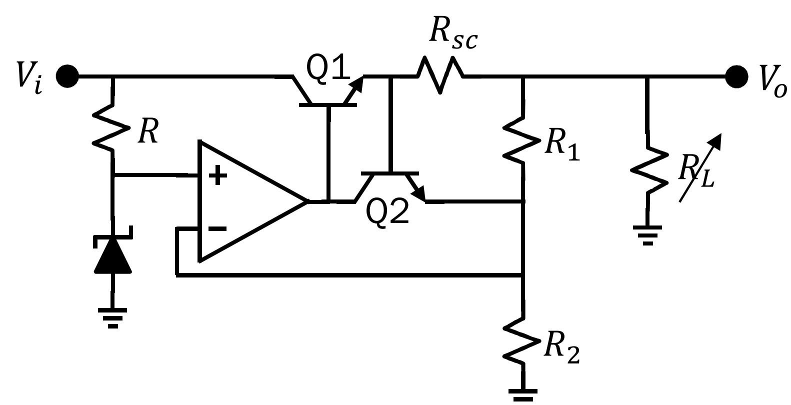
⊖ feedback

$$V_o \nearrow \Rightarrow v^* \nearrow \Rightarrow V_{BE_2} \nearrow \Rightarrow I_2 \nearrow \Rightarrow I_1 \searrow \Rightarrow V_o \searrow$$

$$V_o\left(\frac{R_2}{R_1+R_2}\right) = V_{BE_2} + V_Z$$



$$V_o\left(\frac{R_2}{R_1+R_2}\right) = V_Z$$



$$I_{L_{max}} R_{sc} = V_{BE_{on}}$$

Shunt Voltage Regulators

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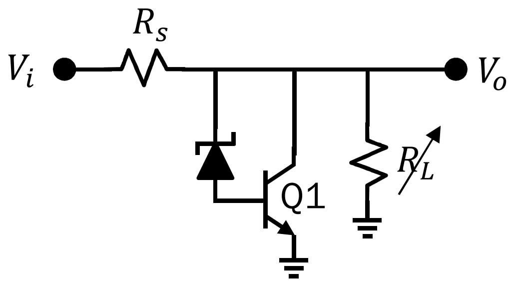

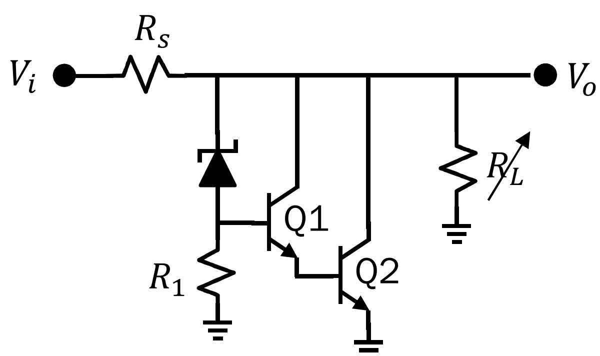

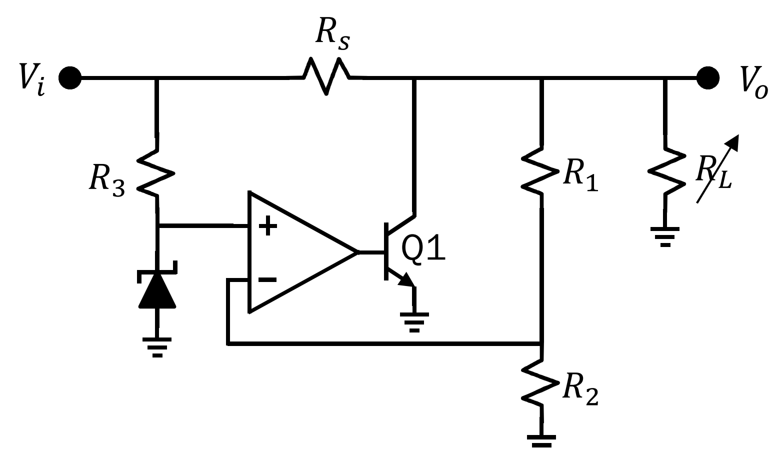

PN junctions , Forward Biased

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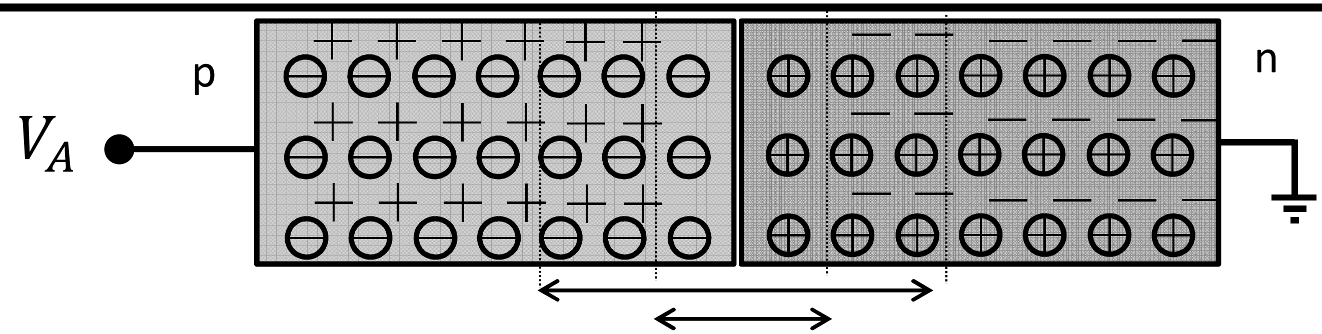
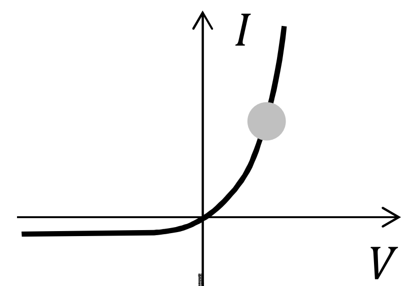
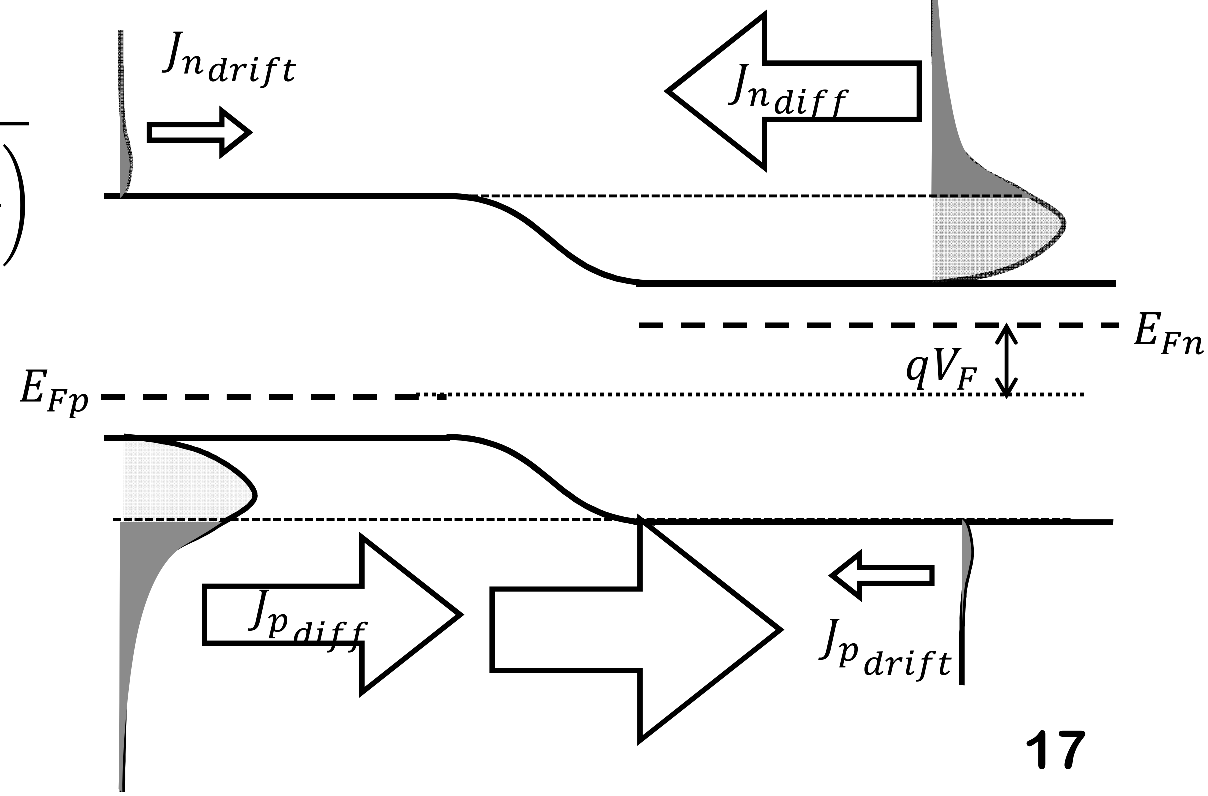
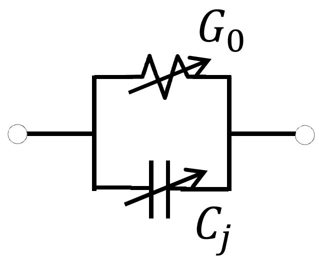




$$W = \sqrt{\frac{2\epsilon_s(V_{bi} - V_A)}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)}$$



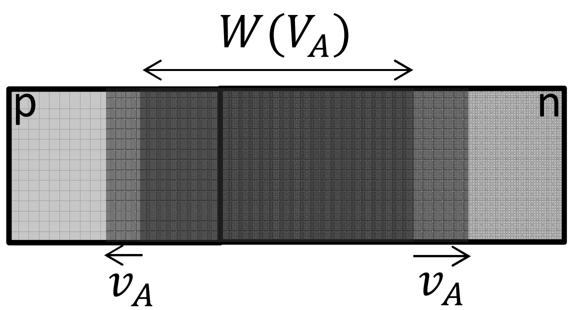
Reverse Bias Admittance



$$Y = G_0 + j\omega C_j$$

C_j : Junction (depletion layer) capacitance
G_0: Reverse bias conductance

A pn junction under reverse bias behaves like a capacitor.
Such capacitors are used in ICs as voltage-controlled capacitors.

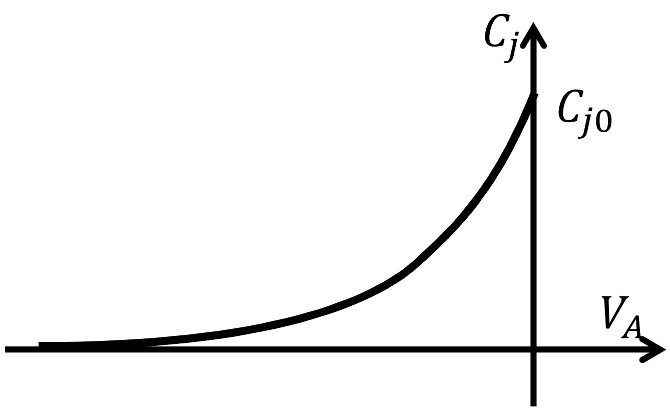


$$W = \sqrt{\frac{2\epsilon_s(V_{bi} - V_A)}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)}$$

$$C_j = \frac{\epsilon_s A}{W} = \frac{C_{j0}}{\left(1 - \frac{V_A}{V_0}\right)^{1/2}}$$

where

$$C_{j0} = \epsilon_s A \Big/ \sqrt{\frac{2\epsilon_s V_{bi}}{q}\left(\frac{1}{N_D} + \frac{1}{N_A}\right)}$$



$$C_j = \frac{C_{j0}}{\left(1 - \frac{V_A}{V_0}\right)^{m}} \quad \begin{cases} m = 1/2 & \text{step junction} \\ m = 1/3 & \text{linear junction} \end{cases}$$

C-V curve is very useful for
characterization of the devices

Reverse Bias Admittance

1. □□□□□□□□
2. □□□□□□□□□□
3. □□□□□□□
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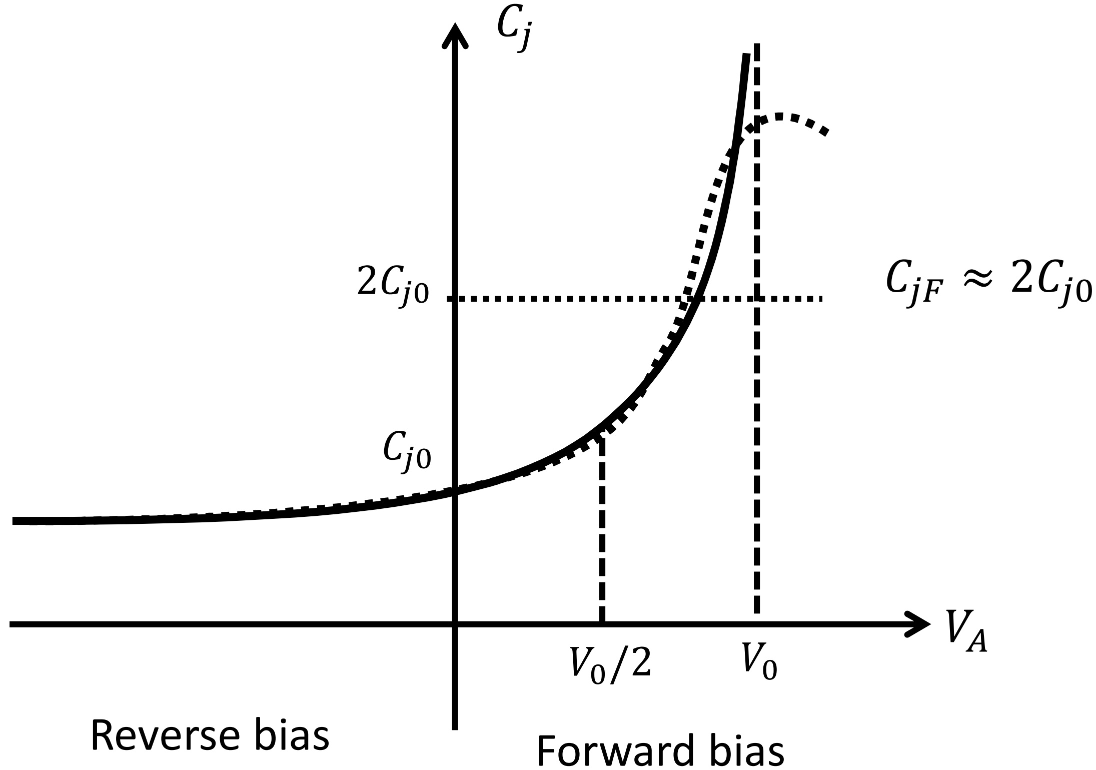

$$C_j = \frac{C_{j0}}{\left(1 - \frac{V_A}{V_0}\right)^m} \quad \begin{cases} m = 1/2 & \text{step junction} \\ m = 1/3 & \text{linear junction} \end{cases}$$

pn Junction: I-V Characteristic

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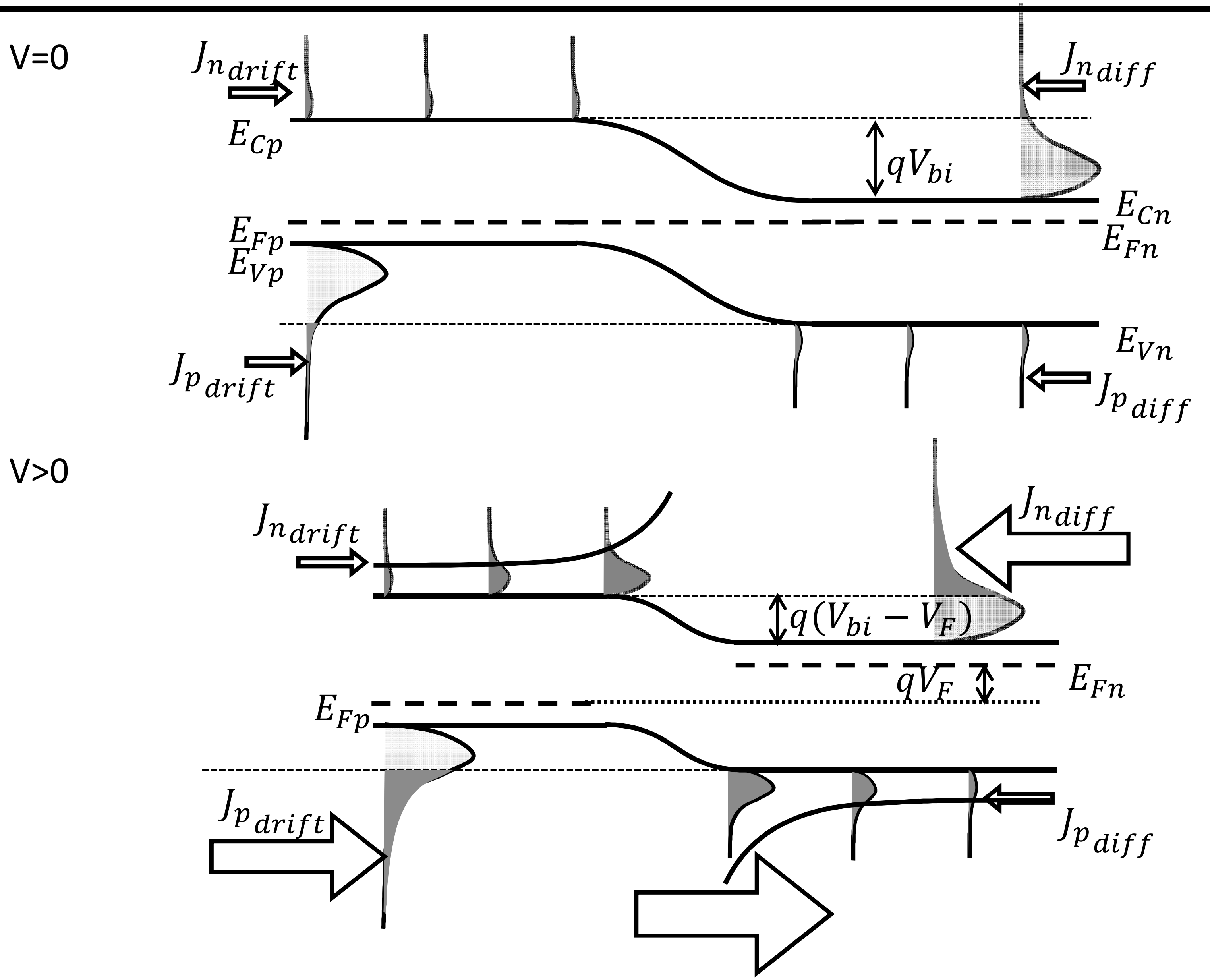
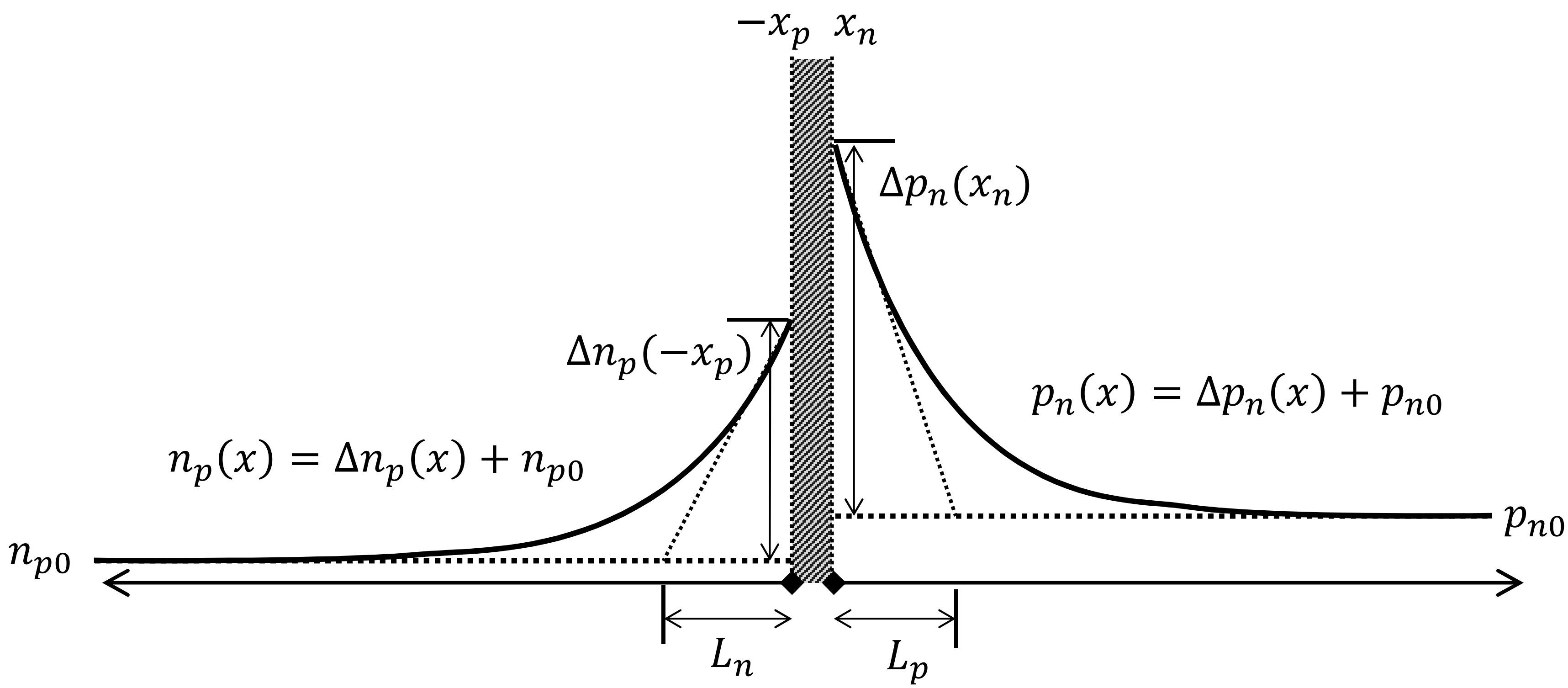


pn Junction: I-V Characteristic

The minority carrier concentrations on either side of the junction under forward bias



$$C_D = \tau_F \frac{i}{v} = \tau_F g_m$$

BJT Small Signal Model (h-π)

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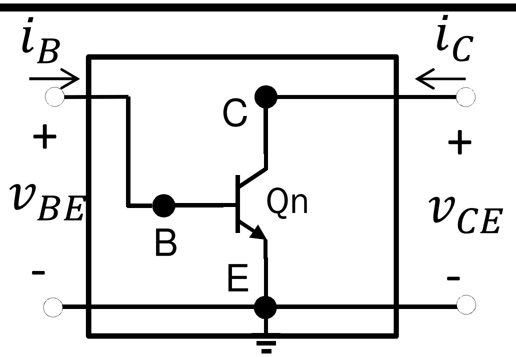
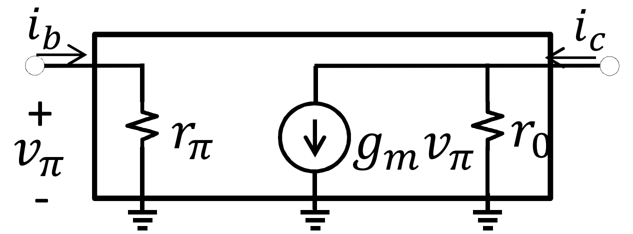


$$i_C = I_S\left(e^{\frac{v_{EB}}{V_T}} - 1\right)\left(1 + \frac{v_{CE}}{V_A}\right)$$

$$\cong \underbrace{I_S e^{\frac{v_{EB}}{V_T}}}_{I_C}\left(1 + \frac{v_{CE}}{V_A}\right)$$



Input resistance:

$$r_\pi \equiv \frac{\partial v_{BE}}{\partial i_B} = \left(\frac{\partial i_B}{\partial v_{BE}}\right)^{-1} = \beta\left(\frac{\partial i_C}{\partial v_{BE}}\right)^{-1} = \beta\left(\frac{I_S}{V_T} e^{\frac{v_{EB}}{V_T}}\right)^{-1} = \beta\frac{V_T}{I_C} = \frac{\beta}{g_m} = \beta r_m$$

Output resistance:

$$r_o \equiv \frac{\partial v_{CE}}{\partial i_C} = \left(\frac{\partial i_C}{\partial v_{CE}}\right)^{-1} = \left(\frac{I_C}{V_A}\right)^{-1} = \frac{V_A}{I_C}$$

Trance-Conductance:

$$g_m \equiv \frac{\partial i_C}{\partial v_{BE}} = \frac{I_S}{V_T} e^{\frac{v_{EB}}{V_T}} = \frac{I_C}{V_T} = \frac{1}{r_m}$$

BJT Small Signal Model (h-π)

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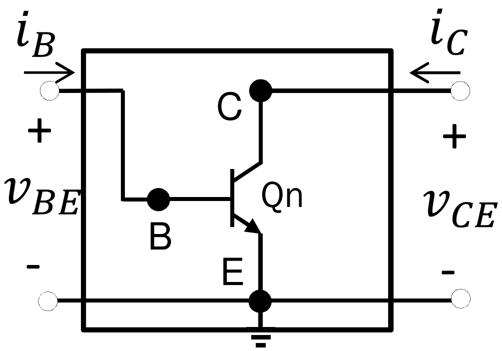

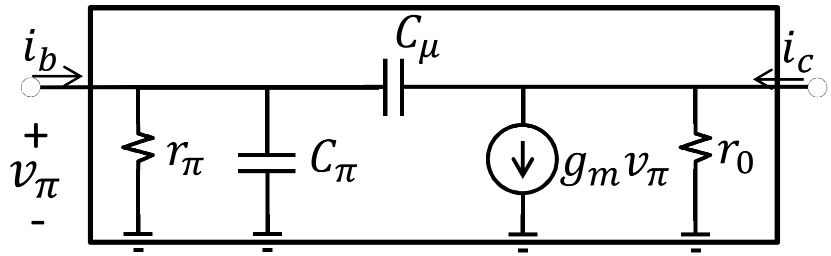

$$r_\pi \equiv \frac{\partial v_{BE}}{\partial i_B} = \frac{\beta}{g_m} = \beta r_m$$

$$r_o \equiv \frac{\partial v_{CE}}{\partial i_C} = \frac{V_A}{I_C}$$

$$g_m \equiv \frac{\partial i_C}{\partial v_{BE}} = \frac{I_C}{V_T}$$

$$C_\pi = C_{je} + C_{De} \approx 2C_{je0} + \tau_F g_m$$

$$C_\mu = C_{jc} = \frac{C_{\mu 0}}{\left(1 - \frac{V_{CB}}{V_{0C}}\right)^m}$$

BJT Small Signal Model (h-π)

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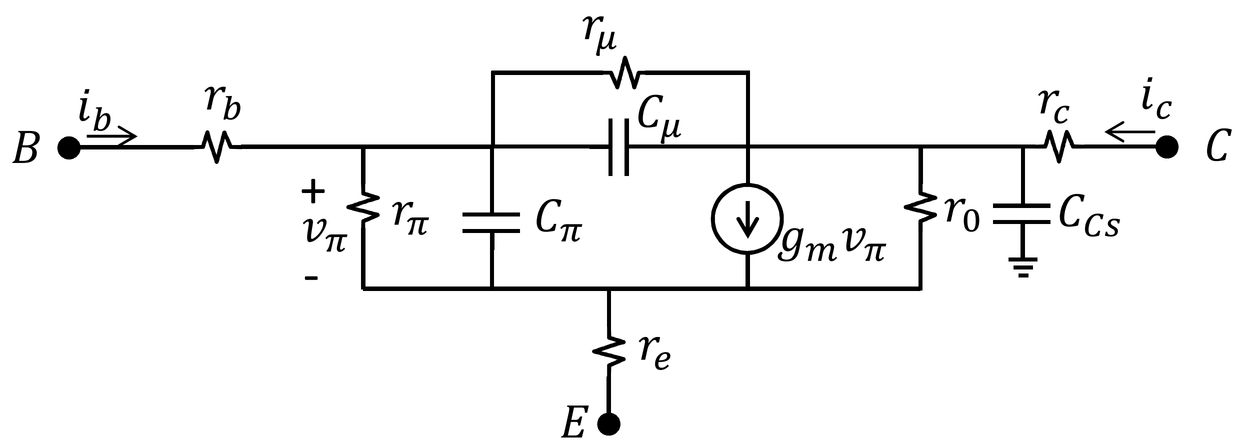

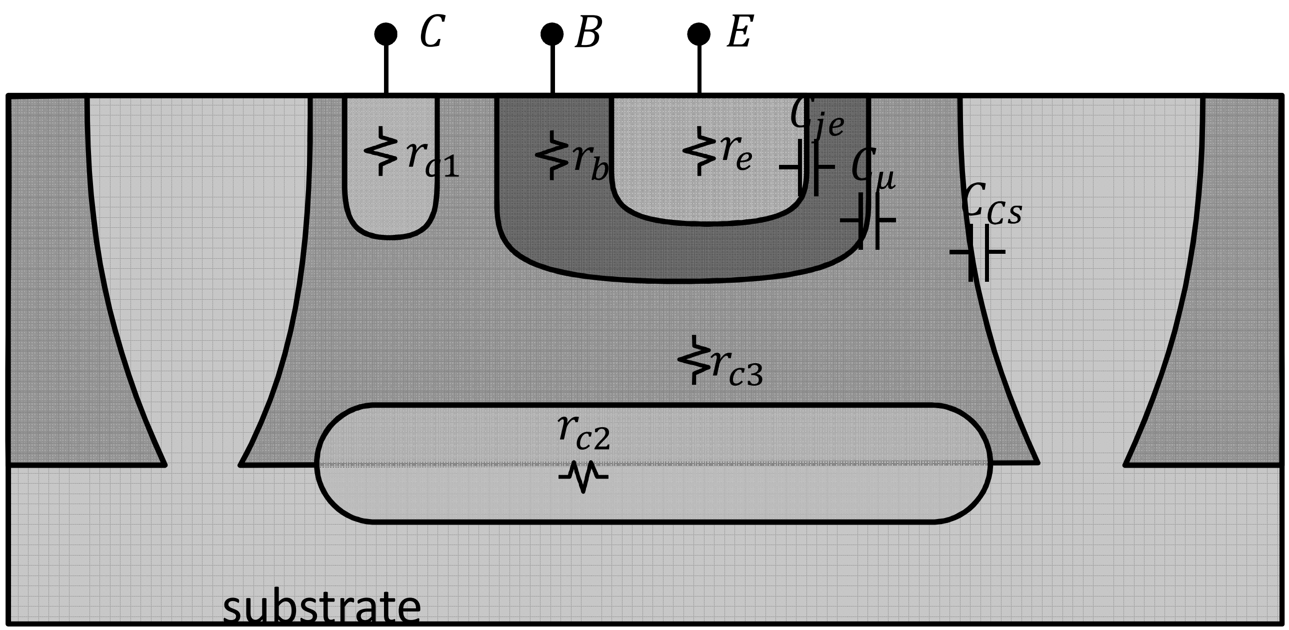

BJT Small Signal Model (h-π)

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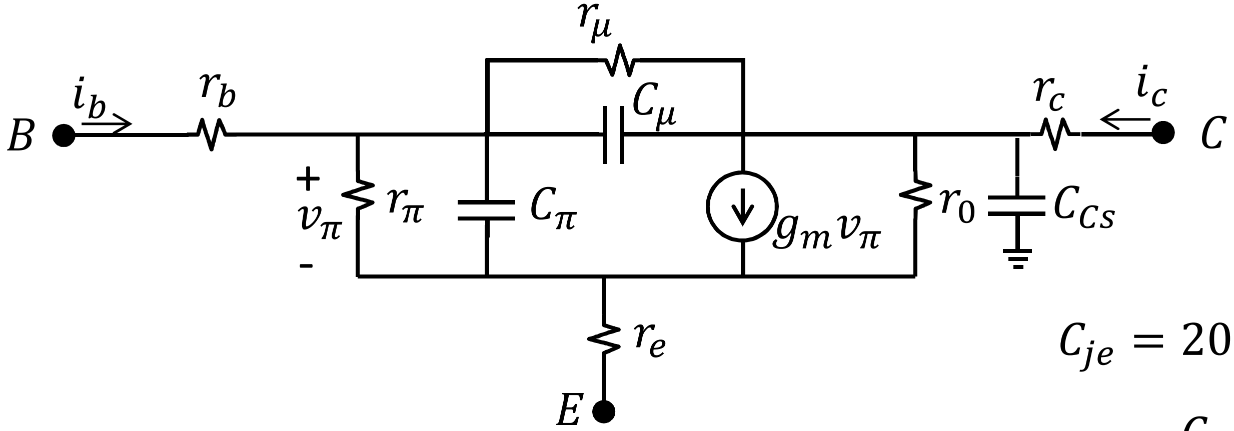


$$g_m = 38^{mmho}$$

$$C_{je} = 20^{fF} \qquad C_b = \tau_F g_m = 0.38^{pF}$$

$$C_\mu = \frac{C_{\mu 0}}{\left(1 - \frac{V_{CB}}{V_{0C}}\right)^{m_c}} = 5.6^{fF}$$

$$C_{Cs} = \frac{C_{Cs0}}{\left(1 - \frac{V_{CB}}{V_{0s}}\right)^{m_s}} = 10.5^{fF}$$

$$C_\pi = 0.02^{pF} + 0.38^{pF} = 0.4^{pF}$$

$$r_\pi = 2.6^{k\Omega} \qquad r_o = 20^{k\Omega} \qquad r_\mu = 20^{M\Omega}$$

$I_C = 1^{mA}$ $\quad V_{CB} = 3^V$ $\quad V_{Cs} = 5^V$

$\beta = 100$ $\quad \tau_F = 10^{ps}$ $\quad V_A = 20^V$

$r_b = 300^\Omega$ $\quad r_c = 50^\Omega$ $\quad r_e = 5^\Omega$

$r_\mu = 10\beta r_o$

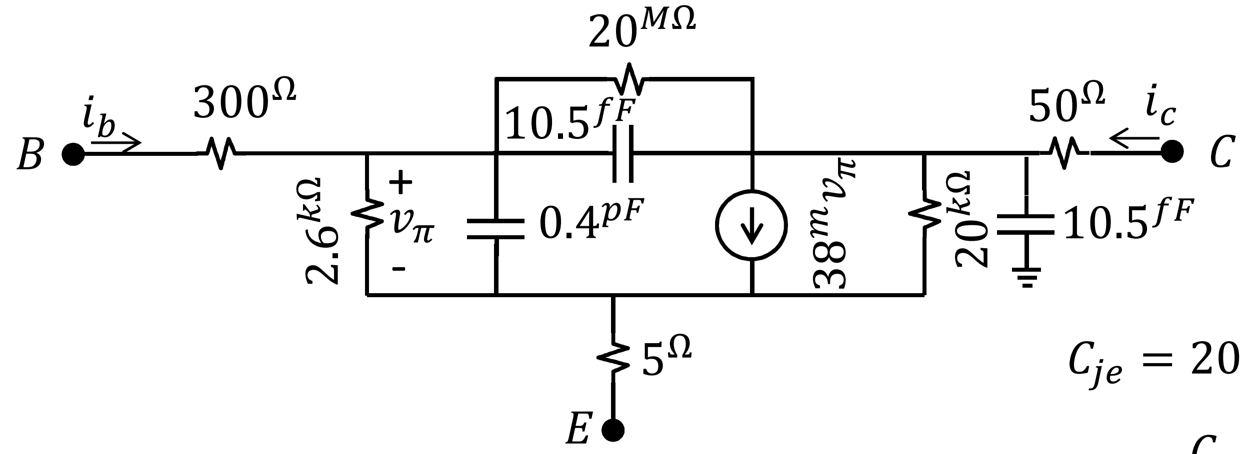
$C_{je0} = 10^{fF}, m_e = 0.5\ , V_{0e} = 0.9^V$

$C_{\mu 0} = 10^{fF}, m_c = 0.3\ , V_{0c} = 0.5^V$

$C_{Cs0} = 20^{fF}, m_s = 0.3\ , V_{0s} = 0.65^V$

1. [illegible]
2. [illegible]
3. [illegible]
4. [illegible]
5. [illegible]

BJT Small Signal Model (h-π)



$g_m = 38^{mmho}$

$C_{je} = 20^{fF}$ $\quad C_b = \tau_F g_m = 0.38^{pF}$

$$C_\mu = \frac{C_{\mu 0}}{\left(1 - \frac{V_{CB}}{V_{0C}}\right)^{m_c}} = 5.6^{fF}$$

$I_C = 1^{mA}$ $\quad V_{CB} = 3^{V}$ $\quad V_{Cs} = 5^{V}$

$\beta = 100$ $\quad \tau_F = 10^{ps}$ $\quad V_A = 20^{V}$

$r_b = 300^{\Omega}$ $\quad r_c = 50^{\Omega}$ $\quad r_e = 5^{\Omega}$

$r_\mu = 10\beta r_o$

$$C_{Cs} = \frac{C_{Cs0}}{\left(1 - \frac{V_{CB}}{V_{0s}}\right)^{m_s}} = 10.5^{fF}$$

$C_\pi = 0.02^{pF} + 0.38^{pF} = 0.4^{pF}$

$C_{je0} = 10^{fF}, m_e = 0.5\,, V_{0e} = 0.9^{V}$

$C_{\mu 0} = 10^{fF}, m_c = 0.3\,, V_{0c} = 0.5^{V}$

$C_{Cs0} = 20^{fF}, m_s = 0.3\,, V_{0s} = 0.65^{V}$

$r_\pi = 2.6^{k\Omega}$ $\quad r_o = 20^{k\Omega}$ $\quad r_\mu = 20^{M\Omega}$

Frequency Response

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2.
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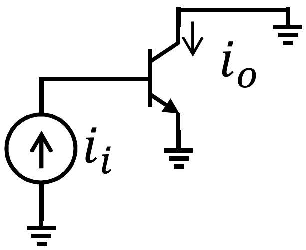
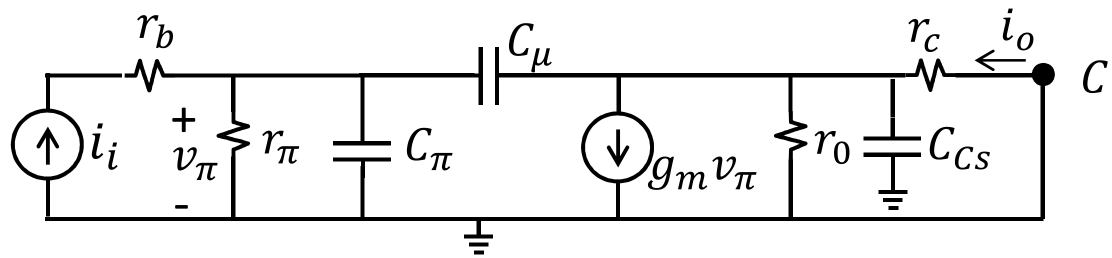
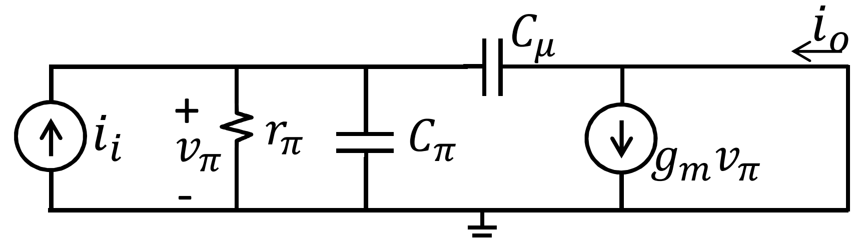
4.
5.





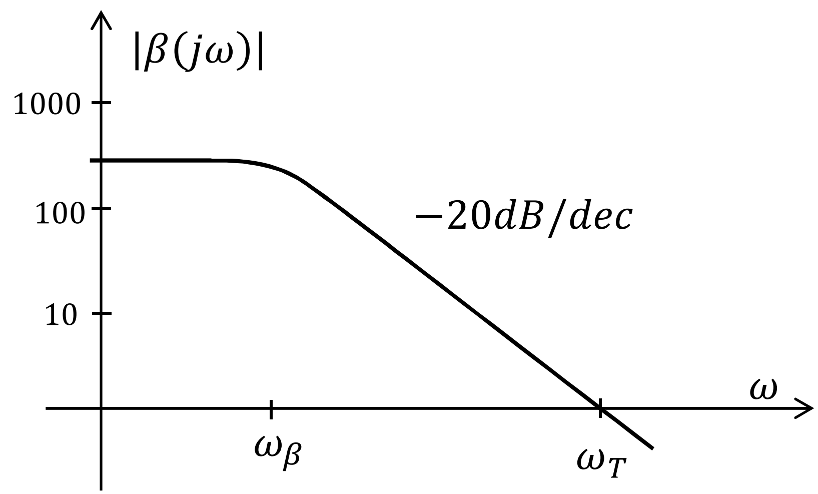


$$\frac{i_o}{i_{in}}(s) = \frac{g_m r_\pi}{1 + r_\pi (C_\pi + C_\mu) s}$$

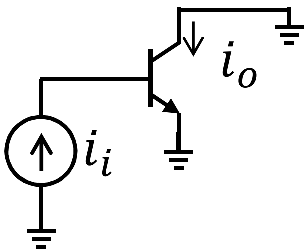
$$\beta(j\omega) = \frac{\beta_0}{1 + \beta_0 \dfrac{C_\pi + C_\mu}{g_m} j\omega}$$

$$\omega_T = \frac{g_m}{C_\pi + C_\mu}$$

$$\omega_\beta = \frac{\omega_T}{\beta_0}$$

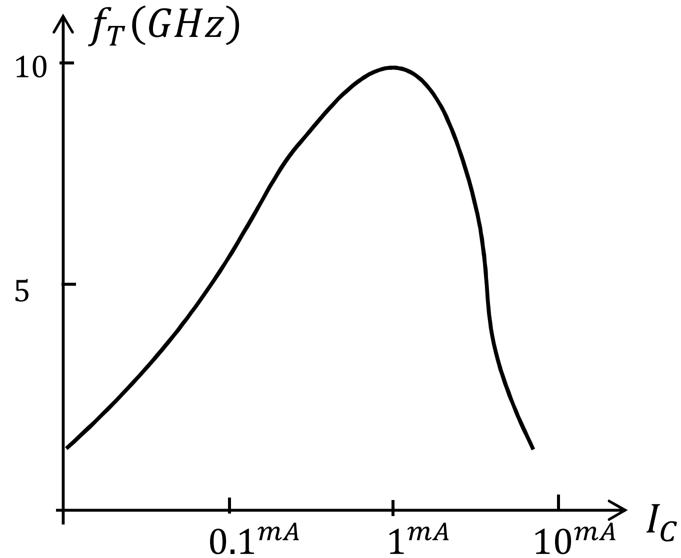


Frequency Response



$$\omega_T = \frac{g_m}{C_\pi + C_\mu}$$

$$\tau_T = \frac{C_\pi + C_\mu}{g_m} = \frac{C_b}{g_m} + \frac{C_\pi}{g_m} + \frac{C_\mu}{g_m} = \tau_F + \frac{C_\pi}{g_m} + \frac{C_\mu}{g_m}$$



Frequency Response

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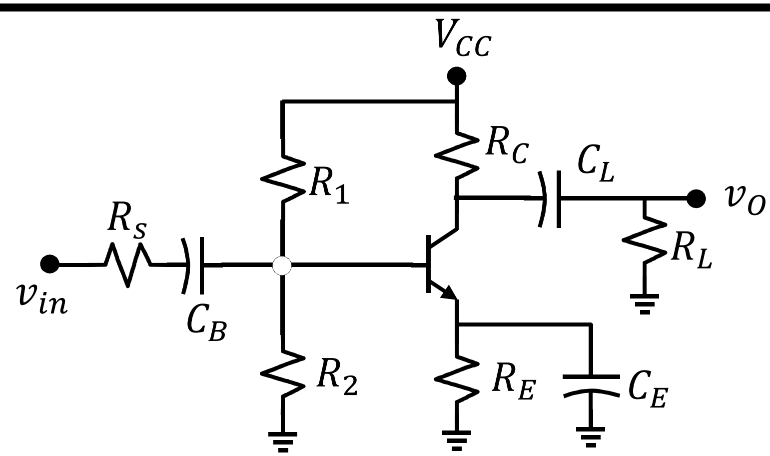

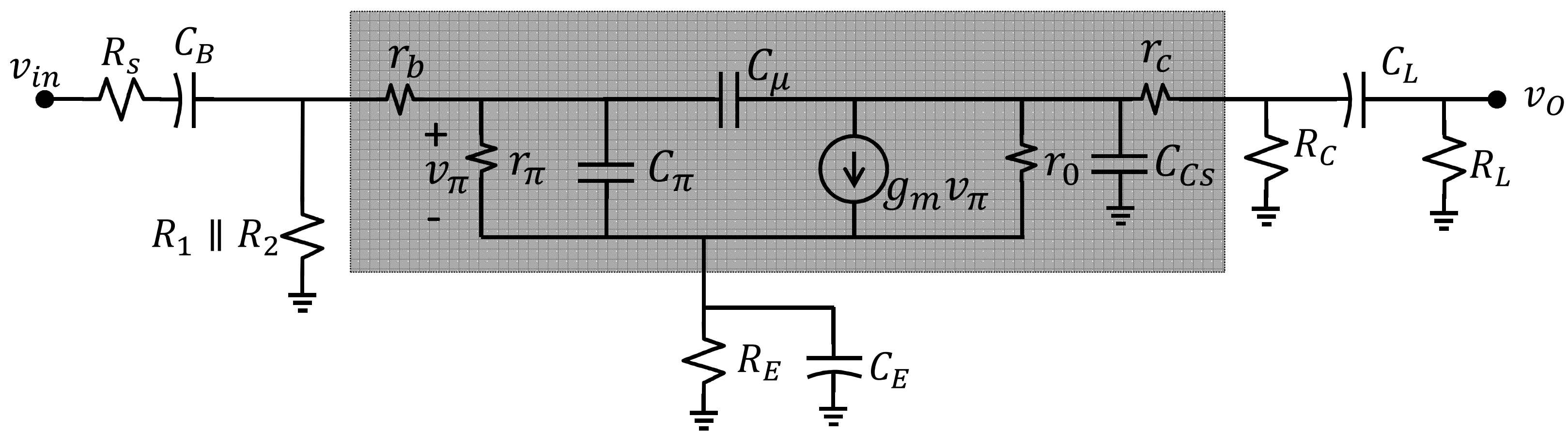

Amplifier Frequency Response

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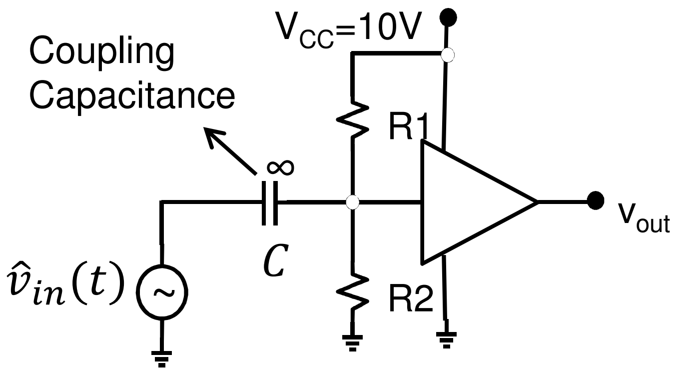
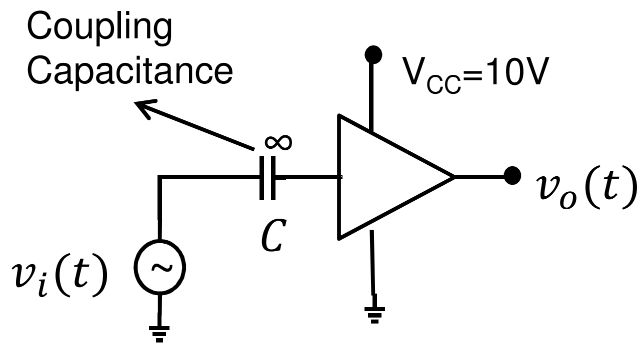




$$v_i(t) = V_i \sin \omega t \qquad v_o(t) = V_o \sin(\omega t + \varphi)$$

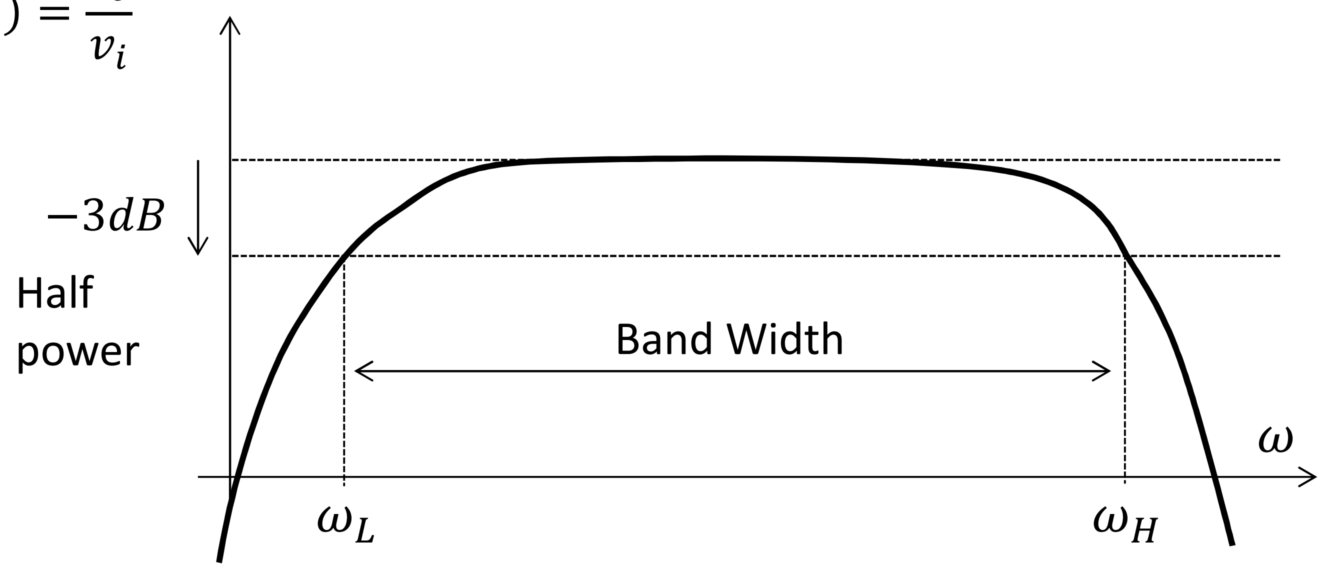
Transfer Function: $T(\omega) = \frac{v_o}{v_i}$

$|T(\omega)| = \frac{V_o}{V_i}$

Amplitude in dB

$\measuredangle T(\omega) = \varphi$

Phase



Amplifier Frequency Response

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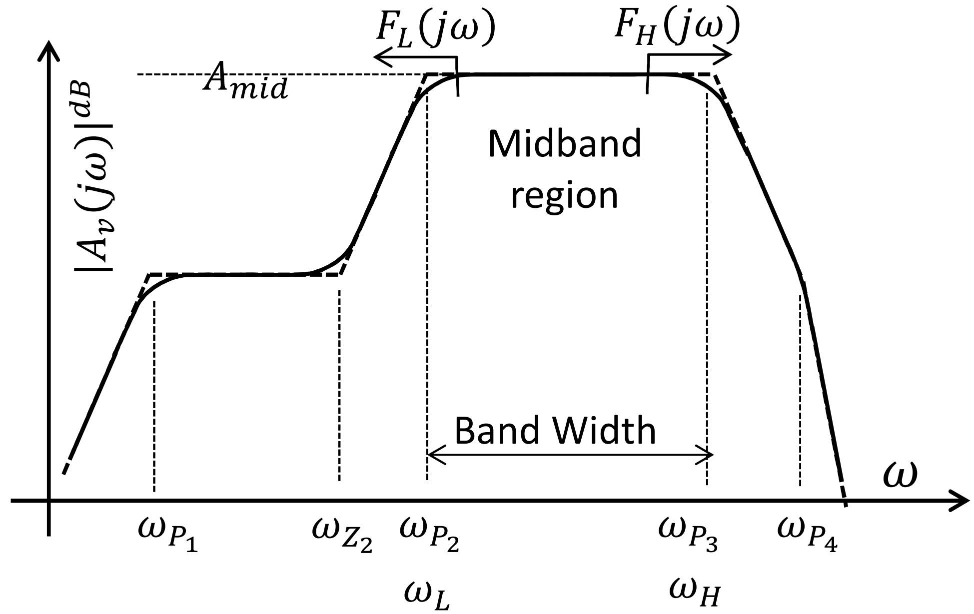
$$A_v(s) = \frac{a_0 + a_1 s + a_2 s^2 + \cdots + a_m s^m}{b_0 + b_1 s + b_2 s^2 + \cdots + b_n s^n}$$

$$= A_{mid} F_L(s) F_H(s)$$

$$F_L(s) = \frac{\left(s+\omega_{Z_1}^L\right)\left(s+\omega_{Z_2}^L\right)\cdots\left(s+\omega_{Z_k}^L\right)}{\left(s+\omega_{P_1}^L\right)\left(s+\omega_{P_2}^L\right)\cdots\left(s+\omega_{P_k}^L\right)}$$

$$F_H(s) = \frac{\left(1+\frac{s}{\omega_{Z_1}^H}\right)\left(1+\frac{s}{\omega_{Z_2}^H}\right)\cdots\left(1+\frac{s}{\omega_{Z_l}^H}\right)}{\left(1+\frac{s}{\omega_{P_1}^H}\right)\left(1+\frac{s}{\omega_{P_2}^H}\right)\cdots\left(1+\frac{s}{\omega_{P_l}^H}\right)}$$



$A_v(s) \cong$

$A_{mid} F_L(s)$ $\quad$ $A_{mid} F_H(s)$

Dominant pole

$\omega_{P_2} \gg \omega_{Z_2}, \omega_{P_1}, \omega_{Z_1}$ $\qquad$ $F_L(s) \cong \dfrac{s}{\left(s+\omega_{P_2}\right)}$ $\qquad$ $\omega_L \cong \omega_{P_2}$

Amplifier Frequency Response

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Absence of Dominant pole $\omega_{P_2} \sim \omega_{Z_2}, \omega_{P_1}, \omega_{Z_1}$

$$A_L(s) = A_{mid} \frac{(s+\omega_{Z_1})(s+\omega_{Z_2})}{(s+\omega_{P_1})(s+\omega_{P_2})} \quad \rightarrow |A_L(j\omega)| = A_{mid} \sqrt{\frac{(\omega^2+\omega_{Z_1})(\omega^2+\omega_{Z_2})}{(\omega^2+\omega_{P_1})(\omega^2+\omega_{P_2})}}$$

$$|A_L(j\omega_L)| = \frac{A_{mid}}{\sqrt{2}} = A_{mid} \sqrt{\frac{(\omega_L^2+\omega_{Z_1})(\omega_L^2+\omega_{Z_2})}{(\omega_L^2+\omega_{P_1})(\omega_L^2+\omega_{P_2})}}$$

$$\omega_L \cong \sqrt{\omega_{P_1}^2 + \omega_{P_2}^2 - 2\omega_{Z_1}^2 - 2\omega_{Z_2}^2}$$

Amplifier Frequency Response

1. [illegible]
2. [illegible]
3. [illegible]
4. [illegible]
5. [illegible]

$$A_v(s) \cong A_{mid} F_H(s)$$

Dominant pole

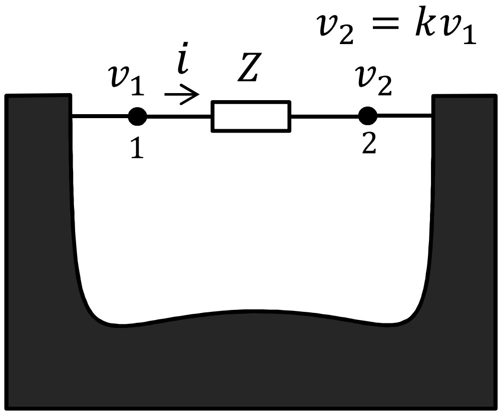
$$F_H(s) \cong \frac{1}{\left(1 + \frac{s}{\omega_{P_3}}\right)} \qquad \omega_H \cong \omega_{P_3}$$

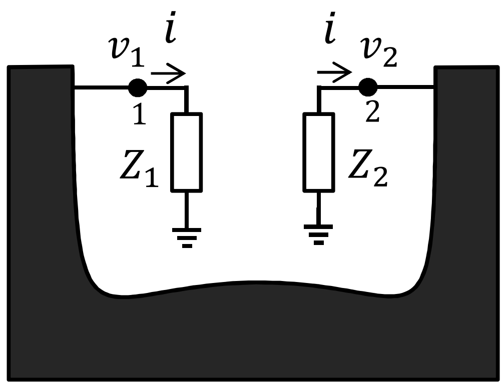
Absence of Dominant pole

$$A_H(s) = A_{mid} \frac{\left(1 + \frac{s}{\omega_{Z_1}}\right)\left(1 + \frac{s}{\omega_{Z_2}}\right)}{\left(1 + \frac{s}{\omega_{P_1}}\right)\left(1 + \frac{s}{\omega_{P_2}}\right)} \rightarrow |A_L(j\omega_H)| = \frac{A_{mid}}{\sqrt{2}} = A_{mid} \sqrt{\frac{\left(1 + \frac{\omega^2}{\omega_{Z_1}^2}\right)\left(1 + \frac{\omega^2}{\omega_{Z_2}^2}\right)}{\left(1 + \frac{\omega^2}{\omega_{P_1}^2}\right)\left(1 + \frac{\omega^2}{\omega_{P_2}^2}\right)}}$$

$$\omega_H \cong \frac{1}{\sqrt{\omega_{P_1}^{-2} + \omega_{P_2}^{-2} - 2\omega_{Z_1}^{-2} - 2\omega_{Z_2}^{-2}}}$$

Miller's Theorem

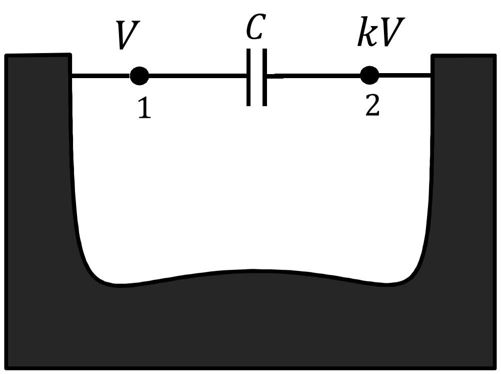


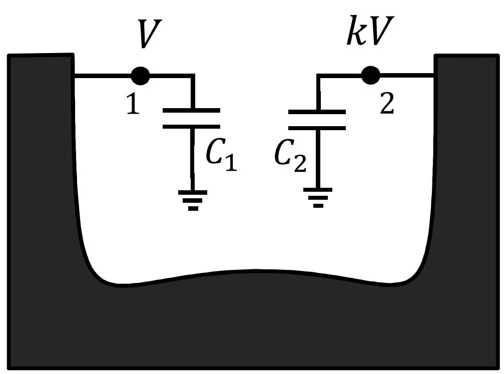


$$i = \frac{v_1 - v_2}{Z}$$

$$i = \frac{v_1}{Z_1} \qquad Z_1 = \frac{Z}{1-k}$$

$$i = \frac{-v_2}{Z_2} \qquad Z_2 = \frac{Z}{1-\frac{1}{k}}$$





$$C_1 = C(1-k)$$

$$C_2 = C(1-\frac{1}{k})$$

Frequency Response

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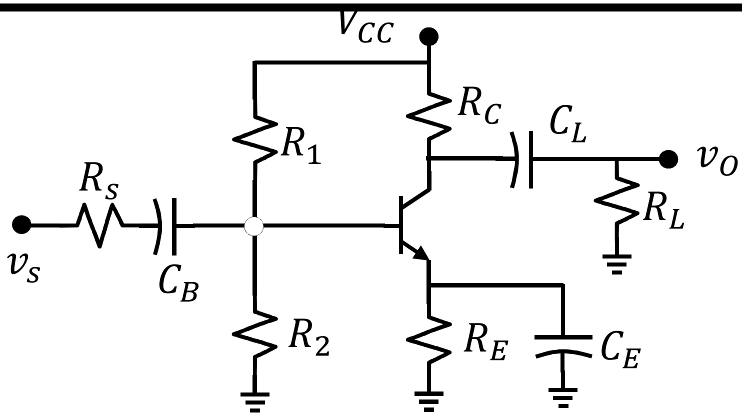
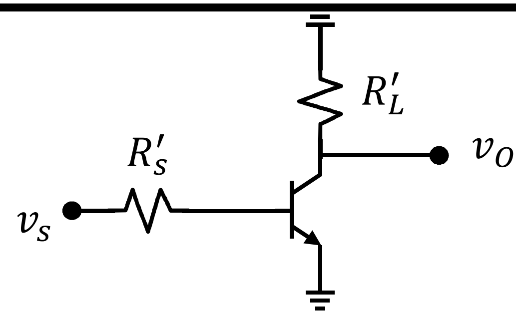
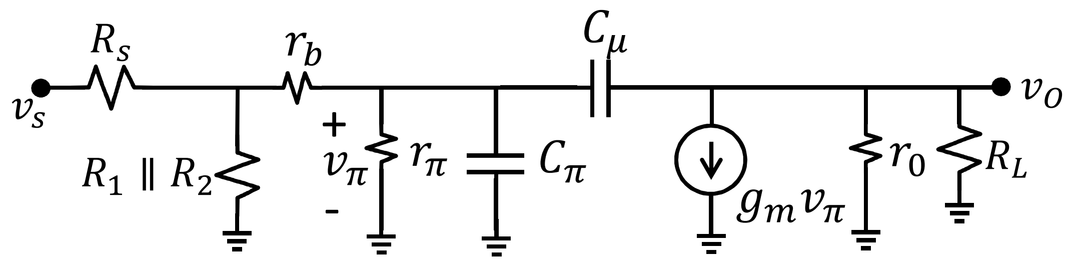


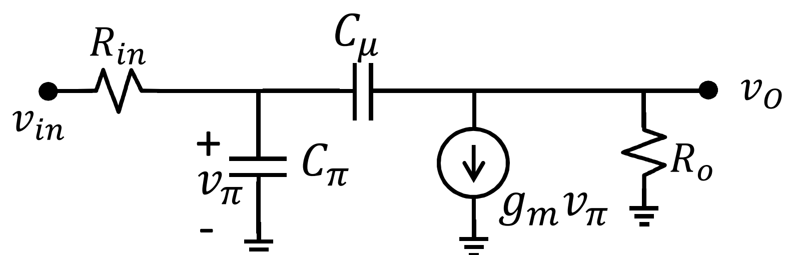




$$R_1 = r_\pi \parallel (r_b + R_1 \parallel R_2 \parallel R_S)$$

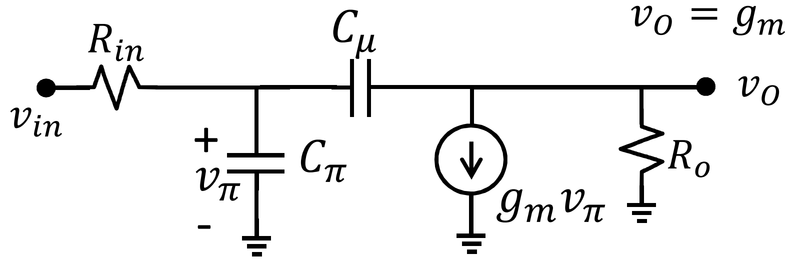
$$v_1 = v_{in} \frac{R_1 \parallel R_2 \parallel (r_b + r_\pi)}{R_s + R_1 \parallel R_2 \parallel (r_b + r_\pi)} \frac{r_\pi}{r_b + r_\pi}$$

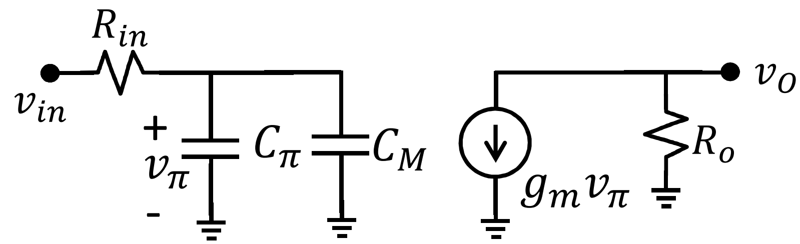
$$R_o = R_L \parallel r_o$$



Frequency Response

$v_O = g_m R_o v_\pi$





$$C_M = C_\mu(1 + g_m R_o)$$

$$p_{in} = 1/\left(R_{in}\left[C_\pi + C_\mu(1 + g_m R_o)\right]\right)$$

KVL-KCL!

$$\frac{v_o}{v_{in}} = -g_m R_o \frac{1 - s\dfrac{C_\mu}{g_m}}{1 + s\left(C_\mu R_o + C_\pi R_{in} + C_\mu R_{in} + g_m R_O R_{in} C_\mu\right) + s^2 R_O R_{in} C_\mu C_\pi}$$

$$p_1 = \frac{1}{R_{in}\left(C_\pi + C_\mu\left(1 + g_m R_o + \dfrac{R_o}{R_{in}}\right)\right)}$$