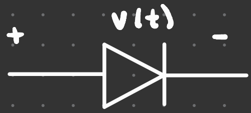
EE CIRCUIT EQUATIONS

BRUKER, shrid's notes

Diode Signal

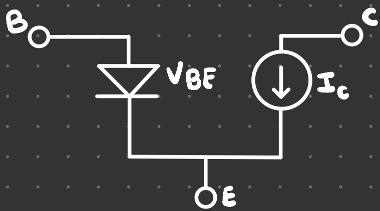


$$v(t) = V_0 + V_p \cos(\omega t)$$

$$I(t) = I_D + \frac{I_D}{V_T} V_p \cos(\omega t)$$

$$I_D = I_S e^{V_0/V_T}$$

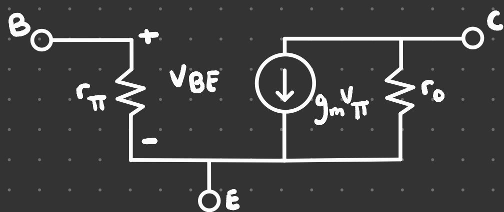
BJT Large Signal



$$V_{BE} = \frac{I_C}{\beta}$$

$$I_C = I_S e^{V_{BE}/V_T}\left(1 + \frac{V_{CE}}{V_A}\right)$$

BJT small signal

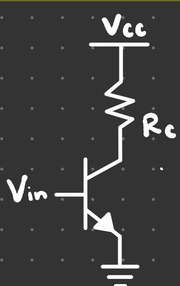


$$r_\pi = \beta / g_m$$

$$g_m = I_C / V_T$$

$$r_o = V_A / I_C$$

common emitter

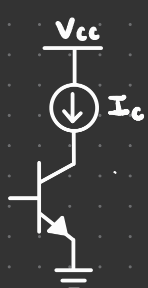


$$r_{in} = r_\pi$$

$$r_{out} = r_o // R_C$$

$$A_v = -g_m (R_C // r_o)$$

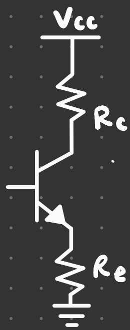
Intrinsic Gain



$$A_v = V_A / V_T$$

Intrinsic Gain is the maximum gain possible if $R_C \to \infty$ w/ Ideal current source

Common emitter w/ Degeneration

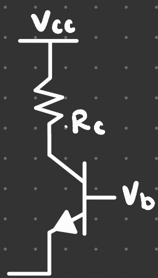


$R_{in} = r_\pi + (\beta+1)R_e$

$R_{out} = R_c \,//\, r_o$

$$A_v = \frac{-R_c \,//\, r_o}{1/g_m + R_e}$$

Common Base

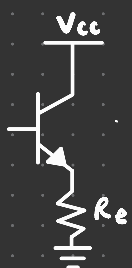


$R_{in} = 1/g_m$

$R_{out} = R_c \,//\, r_o$

$A_v = g_m (R_c \,//\, r_o)$

Common collector / Emittor Follower



$R_{in} = r_\pi + (\beta+1)R_e$

$R_{out} = R_e \,//\, \left(\frac{R_s}{\beta+1} + 1/g_m\right)$, R_s = source impedence

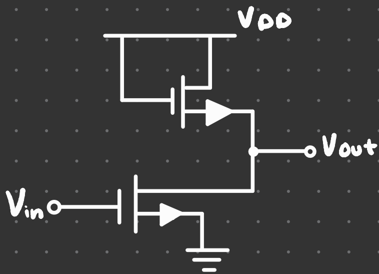
$$A_v = R_e \Big/ \left(\frac{1}{g_m} + R_e\right)$$

Common source

$R_{out} = R_D \,//\, r_o$

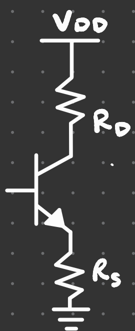
$A_v = -g_m (R_D \,//\, r_o)$

Common Source w/ Diode Load



$$A_v = -\sqrt{\frac{(W/L)_1}{(W/L)_2}}$$

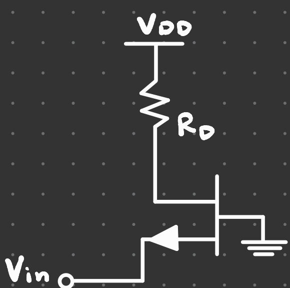
Common Source w/ Degeneration



$$R_{out} = r_o(g_m R_S + 1)$$

$$A_v = \frac{-R_D \,//\, r_o}{(1/g_m + R_S)}$$

Common Gate

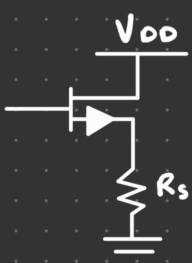


$$R_{in} = 1/g_m$$

$$R_{out} = R_D \,//\, r_o$$

$$A_v = g_m(R_D \,//\, r_o)$$

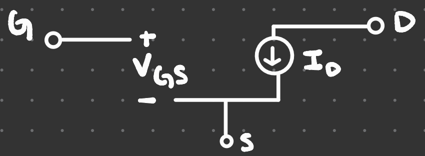
Common Drain (Source Follower)



$$R_{out} = 1/g_m \,//\, r_o \,//\, R_S$$

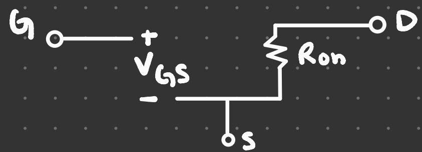
$$A_v = \frac{R_S \,//\, r_o}{1/g_m + R_S \,//\, r_o}$$

Mosfet Large Signal



$V_{DS} > V_{GS} - V_{TH} \rightarrow I_D = ?$

$V_{DS} < V_{GS} - V_{TH} \rightarrow I_D = ?$



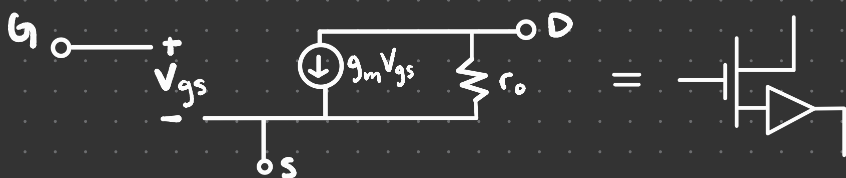
$V_{DS} \ll V_{GS} - V_{TH} \rightarrow I_D = ?$

Saturation $I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})(1+\lambda V_{DS})$

Triode $I_D = \frac{1}{2}\mu_n C_{ox}\frac{W}{L}[2(V_{GS}-V_{TH})V_{DS}+V_{DS}^2]$

Deep Triode $R_{on} = [\mu_n C_{ox}\frac{W}{L}(V_{GS}-V_{TH})]^{-1}$

MOSFET small signal

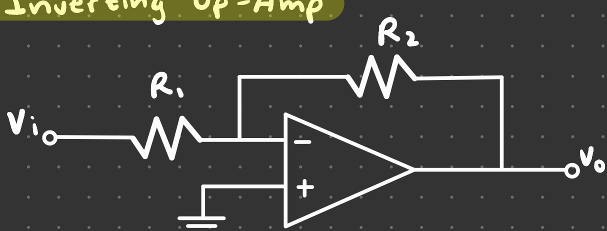


$g_m = \mu_n C_{ox}\frac{W}{L}(V_{gs}-V_{TH})$

$= \sqrt{2\mu_n C_{ox}\frac{W}{L}I_D} = \frac{2I_D}{V_{GS}-V_{TH}}$

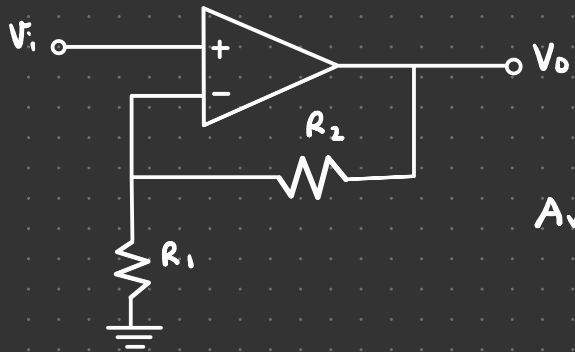
$r_o = \frac{1}{\lambda I_D}$

Inverting Op-Amp



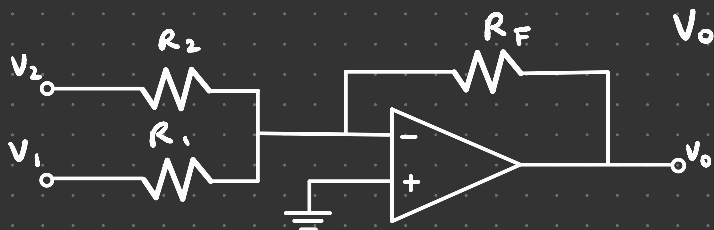
$A_v = \frac{-R_2}{R_1}$

Non-inverting Op-Amp



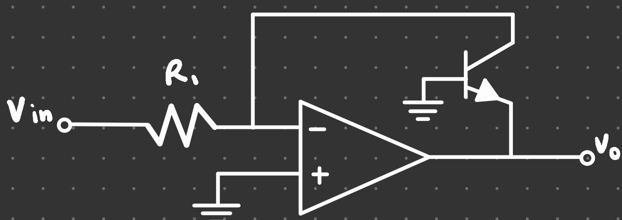
$$A_v = 1 + \frac{R_2}{R_1}$$

Summing Op-Amp



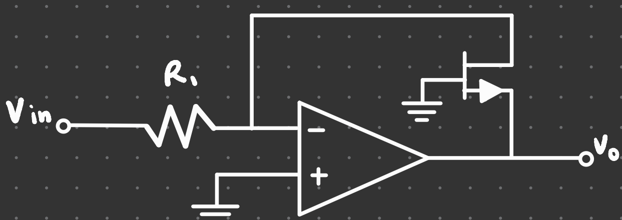
$$V_o = -R_F\left(\frac{V_1}{R_1} + \frac{V_2}{R_2} + \cdots\right)$$

Logarithmic Op-Amp



$$V_o = V_T \ln\left(\frac{V_{in}}{R_1 I_s}\right)$$

Square Root Op-Amp



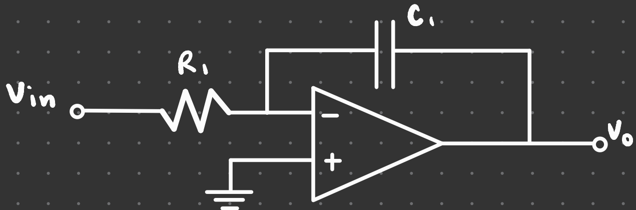
$$V_o = \sqrt{\frac{2V_{in}}{\mu_n C_{ox} \frac{W}{L} R_1}} - V_{TH}$$

Differentiator Op-Amp

$$V_0 = -C_1 R_1 \frac{dV_{in}}{dt}$$

Integrator Op-Amp

$$V_0 = -\frac{1}{C_1} \int_0^T \frac{V_{in}}{R_1}\, dt$$



Bode's Rules

QUESTIONS

* what happens to |H(jw)| at poles and zeroes
* what happens to angle H(jw) at poles and zeroes
* what happens at nodes with an impedance Rj and Cj to ground

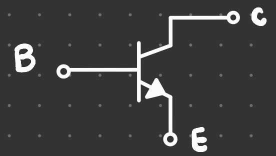
ANSWERS

* poles at w=wpn lower the slope of |H(jw)| by 20dB/decade
* zeroes at w=w2n increase the slope of |H(jw)| by 20dB/decade
* poles create -45 degree shift at w=wp, and approach -90 degree shift at w=10•wp
* zeroes create a +45 degree shift at w=w2, and approach +90 degree shift at w=10•w2

Miller Theorem

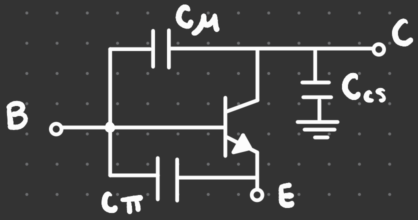
If $A_v = \frac{V_2}{V_1}$, $Z_1 = \frac{Z_F}{1-A_v}$, $Z_2 = \frac{Z_F}{1-1/A_v}$

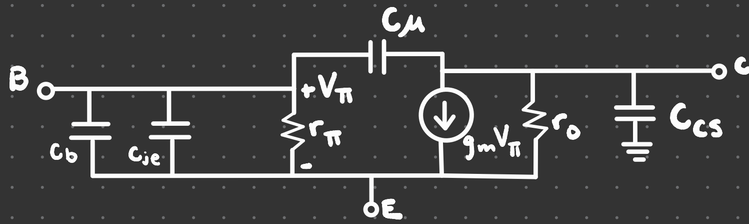
BJT High Frequency



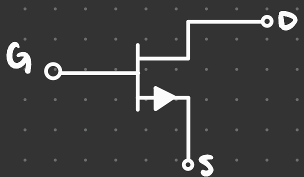
Question: Draw the high frequency small signal model & device parasitics

Answer:

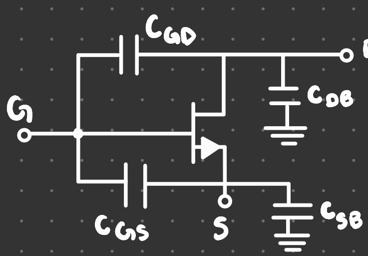


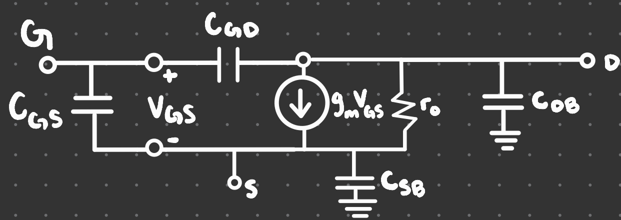


MOSFET High Frequency

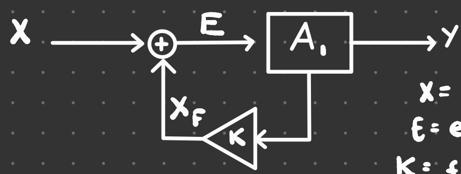


Question: Draw the high frequency small signal model & device parasitics





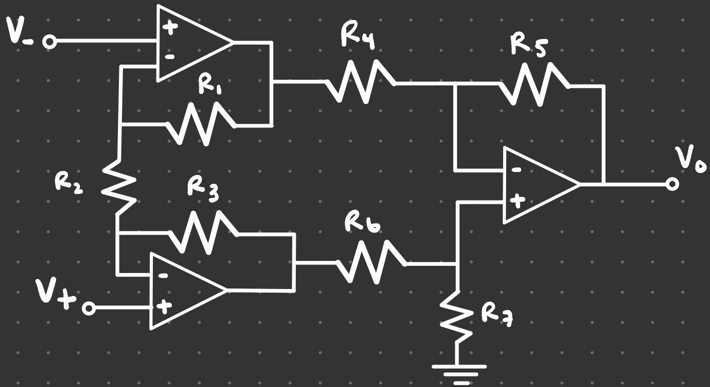
Feedback



- Define X, Y, A_1, K, & E
- $A_v = ?$

X = input, y = output
E = error, A_1 = feedforward factor
K = feedback factor, $A_v = \dfrac{A_1}{(1 + K A_1)}$

Instrumentation Op-Amp

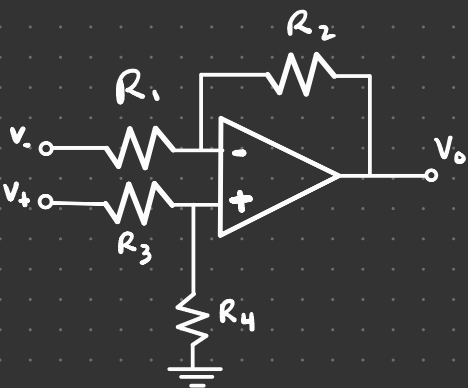


If $R_1 = R_3$

& $\frac{R_5}{R_4} = \frac{R_7}{R_6}$

$$V_o = (V_- - V_+)\left(1 + 2\frac{R_1}{R_2}\right)\frac{R_5}{R_4}$$

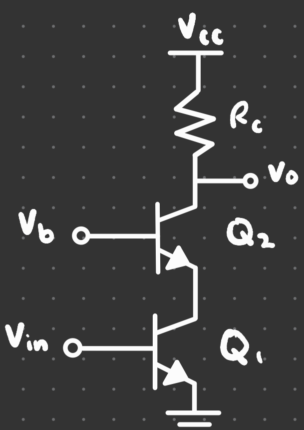
Difference Op-Amp



$$V_o = V_+\left(\frac{R_4}{R_3+R_4}\right)\left(\frac{R_2+R_1}{R_1}\right) - (V_-)\frac{R_2}{R_1}$$

If $\frac{R_2}{R_1} = \frac{R_4}{R_3} = V_o = (V_+ - V_-)\frac{R_2}{R_1}$

BJT Cascode

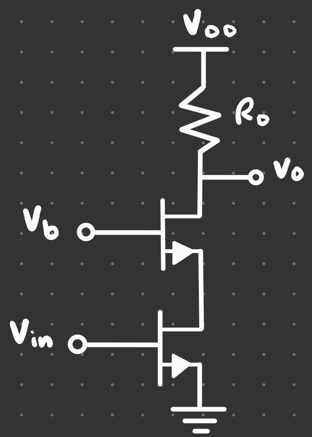


$$R_{in} = r_{\pi_1}$$

$$R_{out} = R_C // [g_{m_2} r_{o2}(r_{o1} // r_{\pi 2}) + (r_{o1} // r_{\pi 2})]$$

$$A_v = -g_{m_1} R_{out}$$

MOSFET Cascode

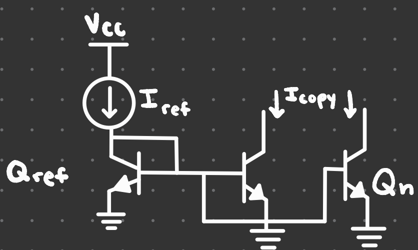


$$R_{in} = \infty$$

$$R_{out} = R_D \,//\, [(1+g_{m1} r_{o1}) r_{o2} + r_{o1}]$$

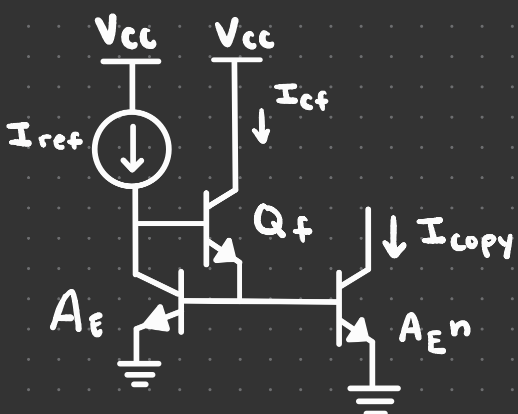
$$A_v = -g_{m1} R_{out}$$

BJT current mirror



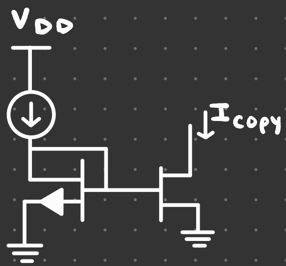
$$I_{copy} = \frac{n I_{ref}}{1 + \frac{1}{\beta}(n+1)}$$

BJT current mirror w/ Feedback



$$I_{copy} = \frac{n I_{ref}}{1 + \frac{1}{\beta^2}(n+1)}$$

MOSFET current mirror



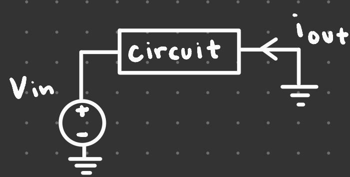
$$I_{copy} = I_{ref}\frac{(W/L)_{copy}}{(W/L)_{ref}}$$

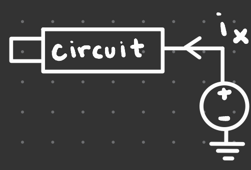
General Amplifier

For a general two part circuit, what is $A_v = ?$

$$A_v = -G_m R_{out}$$

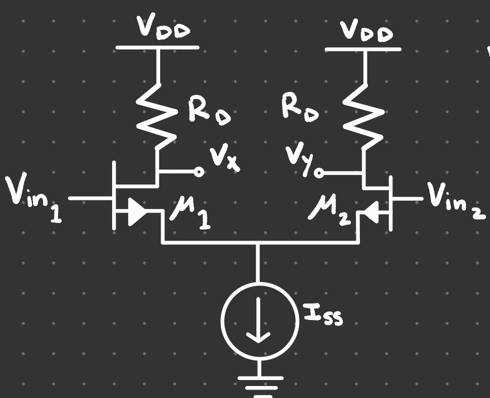
$$G_m = \left.\frac{i_{out}}{V_{in}}\right|_{V_{out}=0} \qquad R_{out} = \left.\frac{V_x}{i_x}\right|_{V_{in}=0}$$





MOSFET Differential Pair

Large Symbol



$$V_x - V_y = -\frac{1}{2} R_D \mu_n C_{ox}\frac{W}{L}(V_{in_1} - V_{in_2})\sqrt{\frac{4I_{SS}}{\mu_n C_{ox}\frac{W}{L}} - (V_{in_1} - V_{in_2})^2}$$

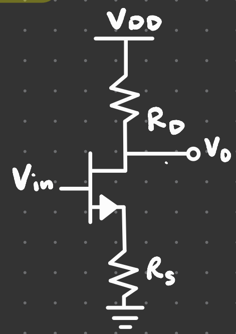
V_x & V_y hit the rails when

$$|V_{in_1} - V_{in_2}| = \sqrt{\frac{2I_{SS}}{\mu_n C_{ox}\frac{W}{L}}}$$

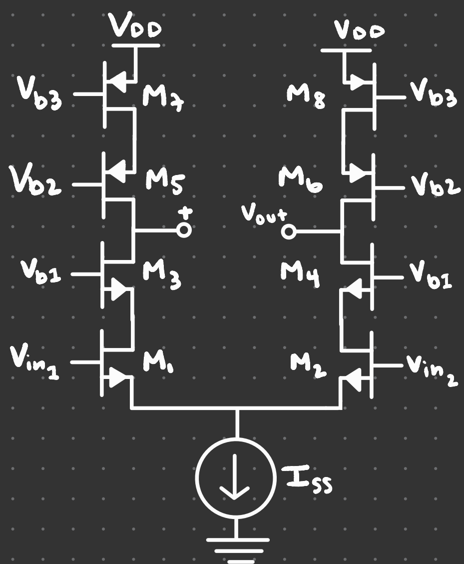
where $I_{D_1} = I_{SS}$

& $I_{D_2} = 0$

MOSFET Differential Pair
small signal



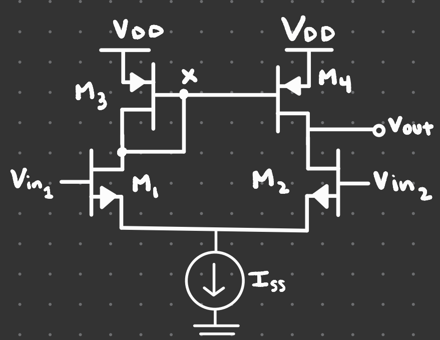
MOSFET Telescopic Differential Pair



$$A_v = -g_{m_1}\left[(g_{m_3} r_{o_3} + 1) r_{o_1} + r_{o_3}\right] // \cdots$$

$$\cdots \left[(g_{m_4} r_{o_4} + 1) r_{o_5} + r_{o_4}\right]$$

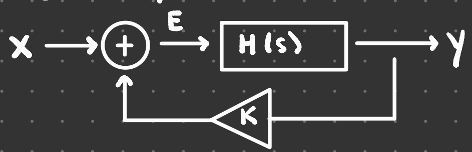
MOSFET Differential w/ Active Load



$$A_v = \frac{V_{out}}{V_{in_1} - V_{in_2}} = g_{m_N}\left(r_{oN} // r_{oP}\right)$$

Bark Hausen's Criteria

Consider System:



system $H(j\omega) = H(s)$ oscillates @ ω_1 where $|KH(j\omega_1)| = 1$ & $\angle KH(j\omega_1) = -180^\circ$

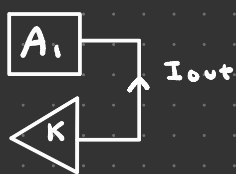
Phase Margin

- Gain crossover ω_{Gx} when $|KH(j\omega)| = 1$
- Phase crossover ω_{px} when $\angle KH(j\omega) = -180^\circ$
- Phase margin is how far away ω_{Gx} is from ω_{px}, i.e. $\angle H(j\omega_{Gx}) + 180^\circ$

Feedback sense-current

How is current output sensed? How is the output impedence affected? Draw current sense diagram

CURRENT IS SENSED IN SERIES

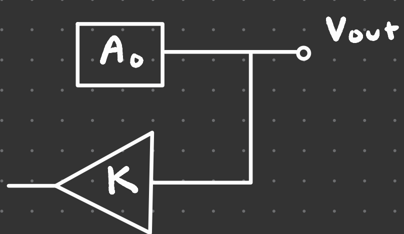


$$Z_r = R_{out}(1 + KA_1)$$

Feedback sense-voltage

How is voltage output sensed? How is the output impedance affected? Draw voltage sense diagram

VOLTAGE IS SENSED IN PARALLEL (SHUNT)

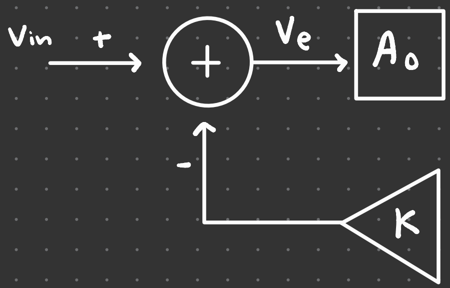


$$Z_r = \frac{R_{out}}{1 + KA_0}$$

Feedback return- voltage

- How is voltage feedback returned?
- How is the input impedance affected?
- Draw voltage return diagram

VOLTAGE IS RETURNED IN SERIES

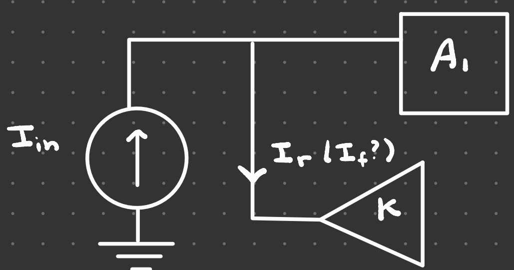


$$Z_r = R_{in}(1 + K A_0)$$

Feedback return- current

- How is current feedback returned?
- How is the input impedance affected?
- Draw current return diagram

CURRENT IS RETURNED IN PARALLEL (SHUNT)



$$Z_r = \frac{R_{in}}{H K A_1}$$

Topics to know

$$y(1 + A_1 K) = A_1 x \rightarrow \frac{y}{x} = \frac{A_1}{1 + A_1 K}, \quad y + A_1 K y = A_1 x, \quad y = A_1 E, \quad E = X - X_F$$

$$X_r = Ky, \quad y = A_1(x - Ky)$$

- summing
- Logarithmic
- square root
- Differential
- Instrumentation
- Differentiator
- Integrator

- High freq. Parasitics
- Miller effect
- cascodes
- current mirrors
- Diff pair

- Feedback topologies
- General def. for Cin & Rout
- Bode's rules
- Transit frequency
- Burkhauser
- stability