23.1 $A_{OL} = 150K \pm 10\%$ v/v $\beta = .1$

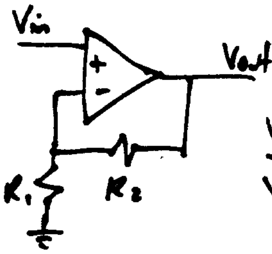
$$A_{CL} = \frac{A_{OL}}{1+A_{OL}\beta} \Rightarrow \frac{dA_{CL}}{dA_{OL}} = \frac{-1}{(1+A_{OL}\beta)^2} \Rightarrow \frac{dA_{CL}}{A_{CL}} = \frac{-dA_{OL}}{(1+A_{OL}\beta)^2} \cdot \frac{(1+A_{OL}\beta)}{A_{OL}}$$

$$\frac{dA_{CL}}{A_{CL}} = \frac{-dA_{OL}}{A_{OL}} \cdot \frac{1}{1+A_{OL}\beta} \Rightarrow \text{\% tolerance } A_{CL} = (-)\text{ \% tolerance } A_{OL} \left(\frac{1}{1+A_{OL}\beta}\right)$$

$$= \mp (.1)\left(\frac{1}{1+(.1)(150k)}\right)$$

$$= \mp .00067\%$$

23.2 non-inverting op-amp:

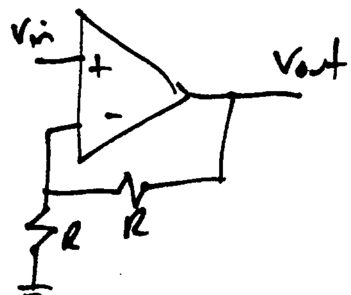


$$\frac{V_{out}}{V_{in}} = \frac{R_1+R_2}{R_1} = \frac{1}{\beta} \quad \{\text{ideal op-amp} \Rightarrow A_{OL} \approx \infty\}$$

$$\Rightarrow \beta = \frac{R_1}{R_1+R_2} \Rightarrow \text{max is } 1 \text{ if } R_2 = \text{very small (zero)}$$

and R_1 = very large (open)

for $\beta = \frac{1}{2} = \frac{R_1}{R_1+R_2} \Rightarrow R_1 = R_2 = R$



23.3 a) $v_o = v_i A_1 A_2 + v_n A_2$ ①

$v_i = v_s - v_f$ ②

$v_f = \beta v_o$ ③

③ into ②: $v_i = v_s - \beta v_o$ ④

④ into ①: $v_o = A_1 A_2 (v_s - \beta v_o) + A_2 v_n$

$v_o = A_1 A_2 v_s - A_1 A_2 \beta v_o + A_2 v_n$

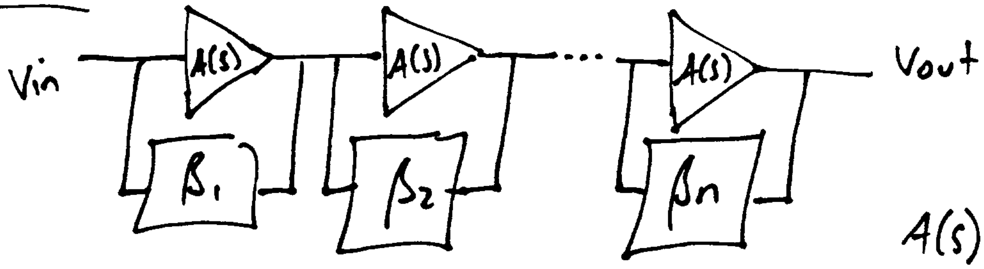
$$\Rightarrow v_o = \frac{A_1 A_2 v_s + A_2 v_n}{1 + A_1 A_2 \beta} = \boxed{\frac{A_1 A_2 v_s}{1 + A_1 A_2 \beta} + \frac{A_2 v_n}{1 + A_1 A_2 \beta}}$$

b) if $\beta = 0 \Rightarrow v_o = A_1 A_2 v_s + A_2 v_n$

c) if $A_1 = A_2 = 200$, what β value is required to reduce v_n by 1/2 as compared to $\beta = 0$?

$$\frac{\cancel{A_2} \cancel{v_n}}{1 + A_1 A_2 \beta} = \frac{\cancel{A_2} \cancel{v_n}}{2} \Rightarrow 1 + (200)^2 \beta = 2 \Rightarrow \beta = \frac{2-1}{(200)^2} = 25 \times 10^{-6}$$

23.4



$$A(s) = \frac{1\,MEG}{s+100}$$

1st stage provides desired pole and want $\frac{V_{out}}{V_{in}} = \frac{1000}{\left(\frac{s}{100,000}+1\right)\left(\frac{s}{400,000}+1\right)^{n-1}}$

1st stage: $$\frac{1\,MEG}{\underbrace{s+100+1\,MEG\cdot\beta_1}_{100,000}} = \frac{A(s)}{1+A(s)\beta_1} = \frac{10}{\left(\frac{s}{100,000}+1\right)}$$

$\Rightarrow$ other stages have identical β's, giving pole @ $\omega = 400,000$ r/s

$$\Rightarrow \frac{1\,MEG}{s+100+1\,MEG\cdot\beta} = \frac{1\,MEG}{400,000}\cdot\frac{1}{\frac{s}{400,000}+1} = \frac{2.5}{\left(\frac{s}{400K}+1\right)}$$

$$\Rightarrow \frac{1000}{\left(\frac{s}{100,000}+1\right)\left(\frac{s}{400,000}+1\right)^{n-1}} = \frac{10\cdot 2.5^{n}}{\left(\frac{s}{100,000}+1\right)\left(\frac{s}{400,000}+1\right)^{n-1}}$$

$$\Rightarrow 2.5^{n-1} = \frac{1000}{10} \Rightarrow n-1 = \frac{\log(100)}{\log(2.5)} \simeq 5$$

$$\Rightarrow \underline{\underline{n=6}}$$

23.5

$$A_{OLL}(s) = 1{,}000 \frac{s}{s+100} \text{ V/V}$$

$$A_{CLL}(s) = \frac{A_{OLL}(s)}{1 + A_{OLL}(s)\beta} = \frac{1{,}000 \frac{s}{s+100}}{1 + 1{,}000 \frac{s}{s+100}\beta} = \frac{1{,}000\, s}{s + 100 + 1{,}000 s\beta}$$

$$= \frac{1{,}000\, s}{s(1+1{,}000\beta)+100} = \left(\frac{1{,}000}{1+1{,}000\beta}\right)\left(\frac{s}{s+\frac{100}{1+1{,}000\beta}}\right)$$

and want in form: $A_{CLL}(\text{midband})\left(\frac{s}{s+\omega_{LCL}}\right) = A_{CLL}(\text{mid})\left(\frac{s}{s+50}\right)$

$$\Rightarrow \frac{100}{1+1{,}000\beta} = 50 \Rightarrow 1{,}000\beta + 1 = 2 \Rightarrow \underline{\beta = .001}$$

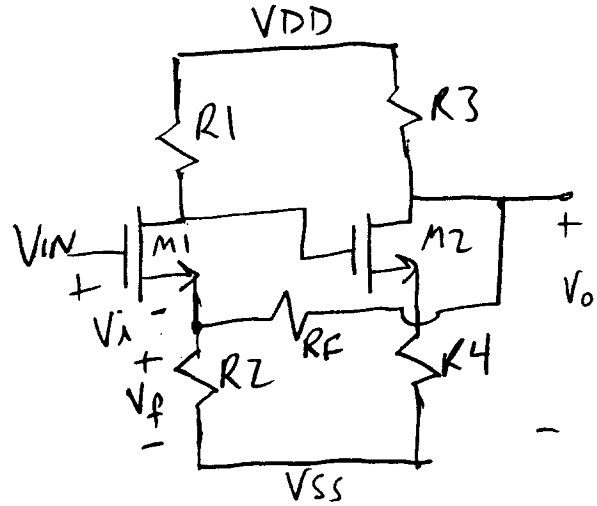
and $A_{CLL}(\text{mid}) = \dfrac{1{,}000}{1+(1{,}000)(.001)} = 500 \text{ V/V}$

23.6

fb topology	i/p var	o/p var	A_{OL} units	β units	$R_{\beta i}$ method	$R_{\beta o}$ method	A_{CL}	R_{if}	R_{of}
Series-Shunt	Volts	Volts	V/V	V/V	Short o/p to gnd; $R_{\beta i}$ = input into β network	"out-of-socket" input device	$A_{CL} = \frac{A_{OL}}{1+A_{OL}\beta}$	$R_{if} = R_i(1+A_{OL}\beta)$	$R_{of} = \frac{R_o}{1+A_{OL}\beta}$
Series-Series	Volts	Amps	A/V	V/A	"out-of-socket" o/p device	"out-of-socket" i/p device	$A_{CL} = \frac{A_{OL}}{1+A_{OL}\beta}$	$R_{if} = R_i(1+A_{OL}\beta)$	~~$R_{of} = \frac{R_o}{1+A_{OL}\beta}$~~ $R_{of} = R_o(1+A_{OL}\beta$
Shunt-Shunt	Amps	Volts	V/A	A/V	Short o/p to gnd	Short i/p to gnd	$A_{CL} = \frac{A_{OL}}{1+A_{OL}\beta}$	$R_{if} = \frac{R_i}{1+A_{OL}\beta}$	$R_{of} = \frac{R_o}{1+A_{OL}\beta}$
Shunt-Series	Amps	Amps	A/A	A/A	"out-of-socket" o/p device	Short i/p to gnd	$A_{CL} = \frac{A_{OL}}{1+A_{OL}\beta}$	$R_{if} = \frac{R_i}{1+A_{OL}\beta}$	$R_{of} = R_o(1+A_{O}$

23.7

a) Series-Shunt

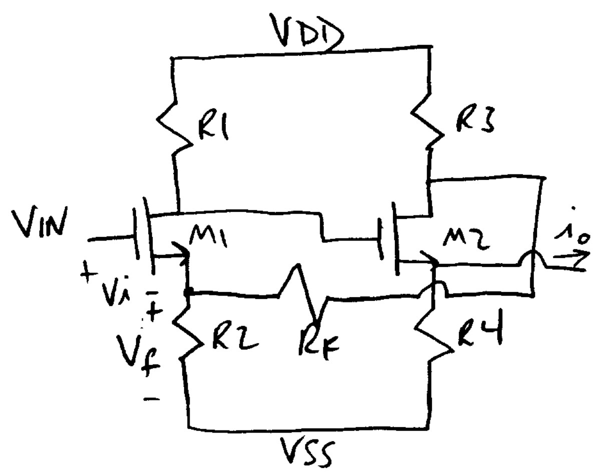


Fwd Path   M1 gate → M1 drain/M2 gate → M2 drain

Fb Path   M2 drain → M1 source via RF

⇒ 2 inversions for (-) fb w/ Series mixing

b) Series - Series



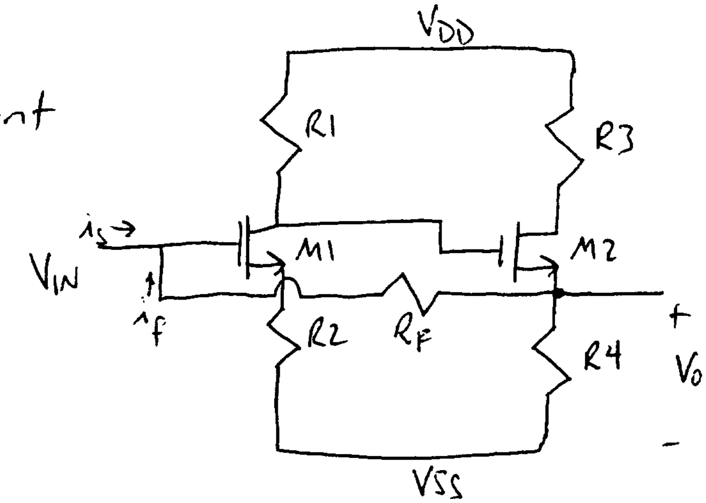
Fwd Path   M1 gate → M1 drain/M2 gate → M2 source

Fb Path   M2 drain → M1 source via RF

⇒ 2 inversions for (-) fb w/ Series mixing

23.7

c) Shunt-shunt

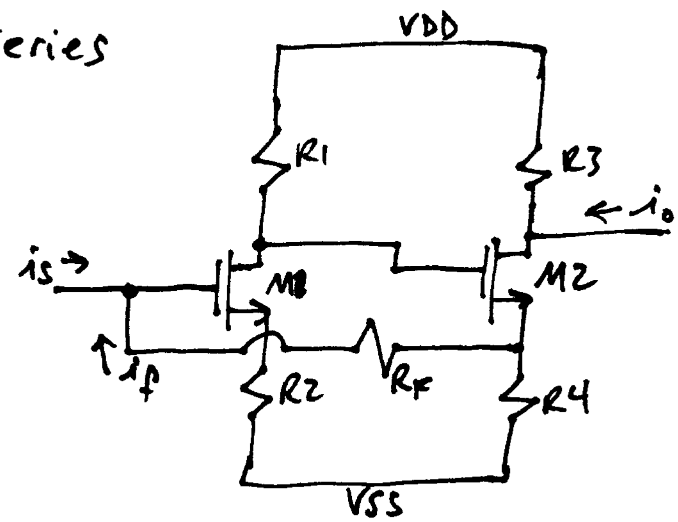


Fwd Path M1 gate → M1 drain/M2 gate → M2 source

Fb Path M2 source → M1 gate via R_F

⇒ 1 inversion for (−) fb w/ shunt mixing

23.7 d) Shunt-series



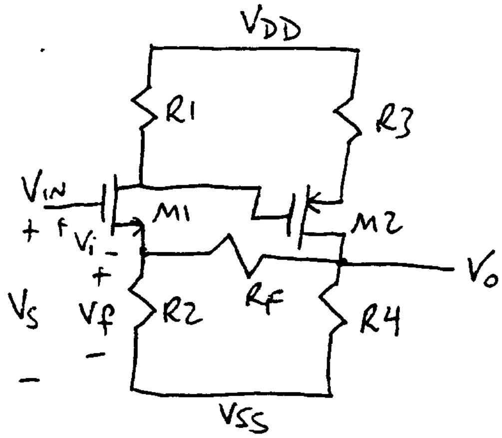
Fwd Path M1 gate → drain
M2 gate → drain

Fb Path M2 source → M1 gate via R_F

⇒ 1 inversion for (−) fb w/ shunt mixing

23.8

a) Series - Shunt



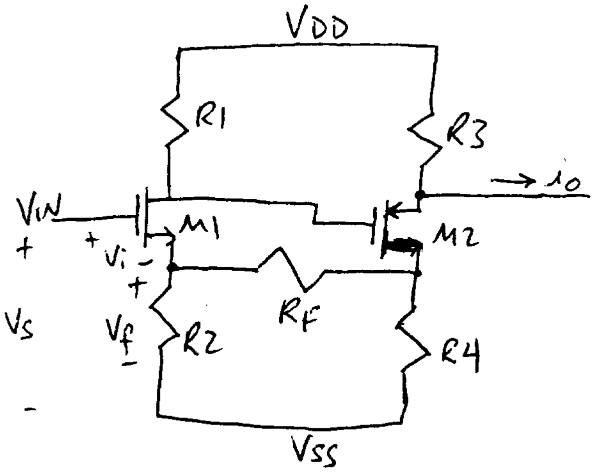
Fwd Path M1 gate → M1 drain / M2 gate → M2 drain

Fb Path M2 drain → M1 source via RF

⇒ 2 inversions for (-) fb w/ series mixing

23.8

b) Series - Series

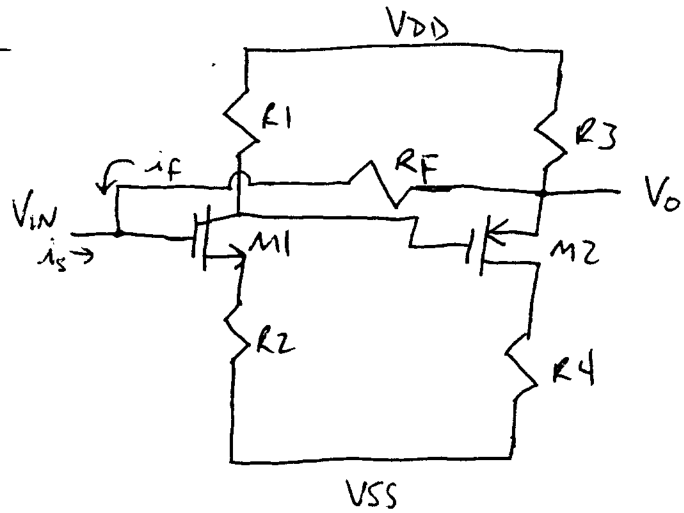


<u>Fwd Path</u> M1 gate → M1 drain/M2 gate → M2 drain

<u>Fb Path</u> M2 drain → M1 source via RF

⇒ 2 inversions for (-) fb w/ series mixing

c) Shunt - Shunt

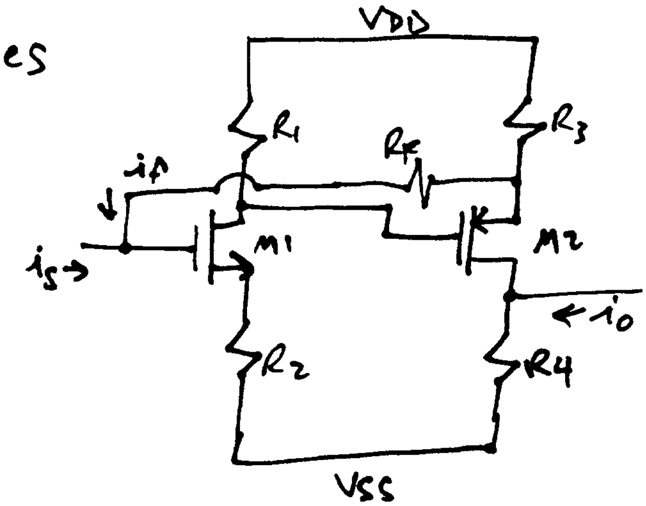


<u>Fwd Path</u> M1 gate ⇒ M1 drain → M2 source

<u>Fb Path</u> M2 source → M1 gate via RF

⇒ 1 inversion for (-) fb w/ Shunt mixing

23.8 d) Shunt-Series



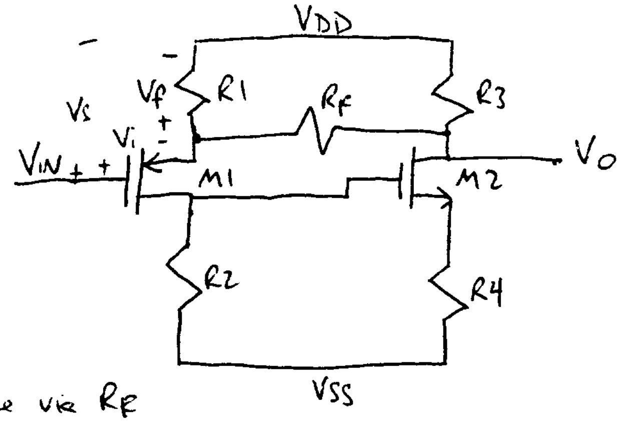
Fwd Path   M1 gate → drain, M2 gate → drain

Fb Path   M2 source → M1 gate via R_F

1 inversion for (−) fb w/ shunt mixing

23.9

a) Series - Shunt

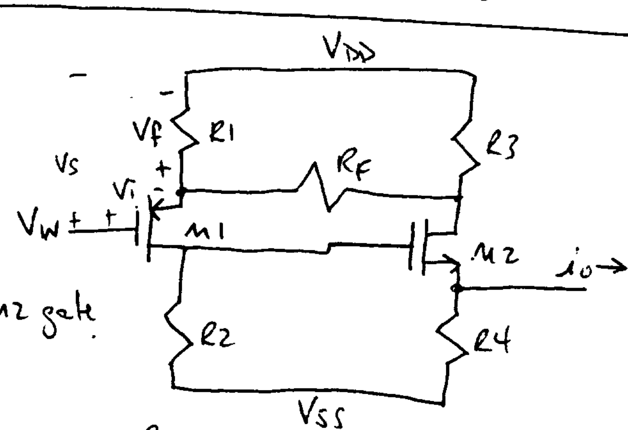


Fwd Path: M1 gate → M1 drain → M2 drain

Fb Path: M2 drain → M1 source via RF

⇒ 2 inversions for (−) fb w/ series mixing

b) Series - Series

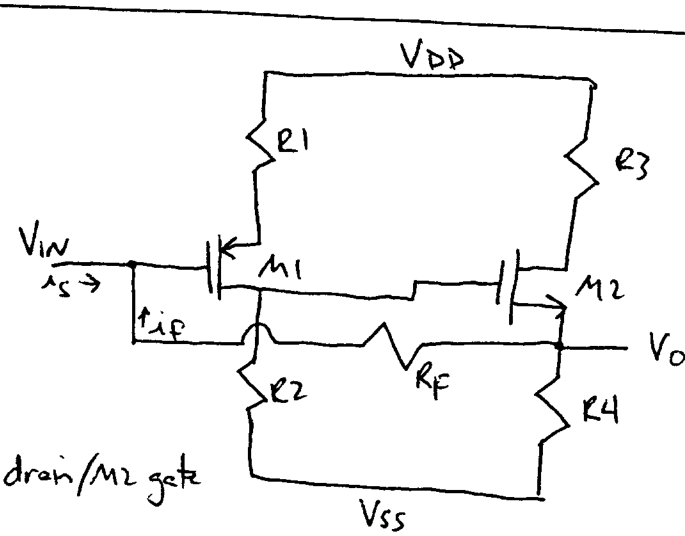


Fwd Path: M1 gate → M1 drain/M2 gate → M2 source

Fb Path: M2 drain → M1 source via RF

⇒ 2 inversions for (−) fb w/ series mixing

c) Shunt- shunt

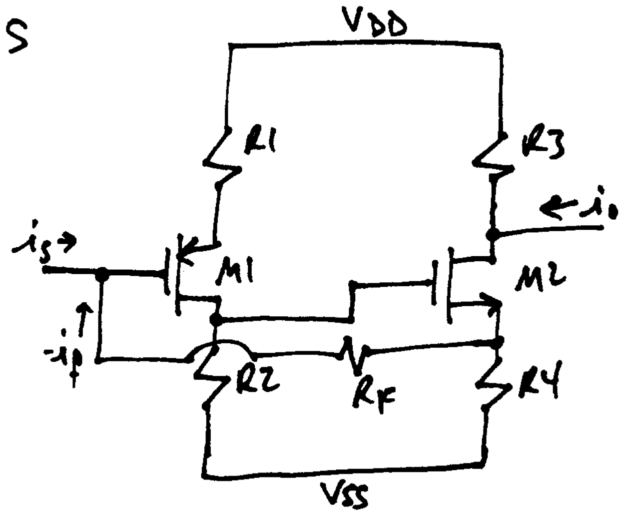


Fwd Path: M1 gate → M1 drain/M2 gate → M2 Source

Fb Path: M2 Source → M1 gate via RF

⇒ 1 inversion for (−) fb w/ shunt mixing

23.9 d) Shunt-Series



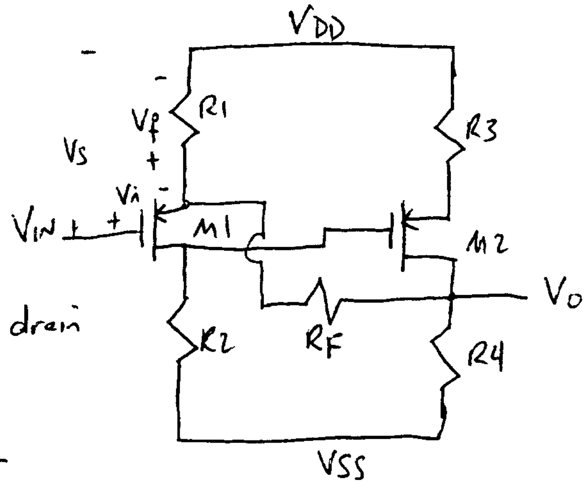
Fwd Path M1 gate-drain
M2 gate-drain

Fb Path M2 source → M1 gate via RF

1 inversion for (-) fb w/ shunt mixing

23.10

a) Series-~~Series~~ Shunt



Fwd Path

M1 gate → M1 drain/M2 gate → M2 drain

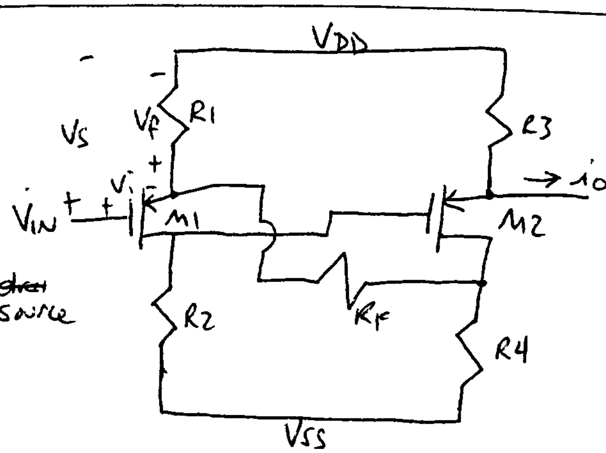
Fb Path

M2 drain → M1 source via RF

⇒ 2 inversions for (−) fb w/ series mixing

---

b) Series - series



Fwd Path

M1 gate → M1 drain/M2 gate → M2 ~~drain~~ source

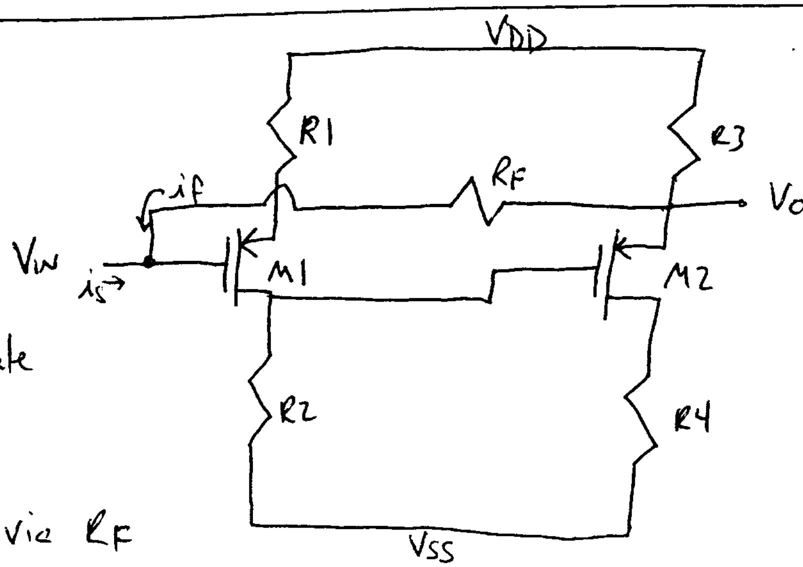
Fb Path

M2 drain → M1 source via RF

⇒ 2 inversions for (−) fb w/ series mixing

---

c) Shunt - shunt



Fwd Path

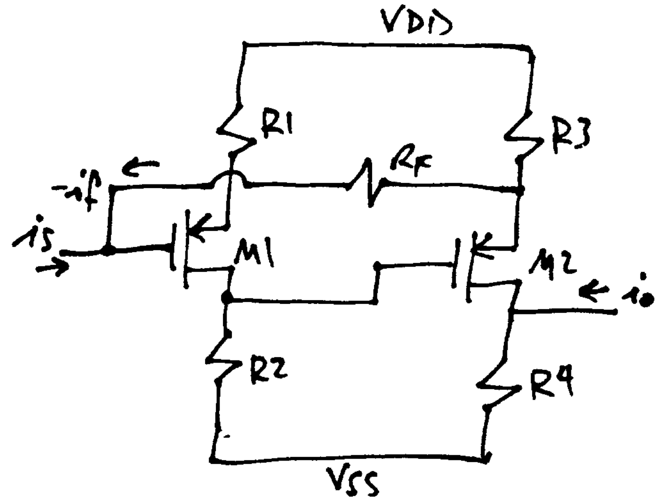
M1 gate → M1 drain/M2 gate
→ M2 source

Fb Path

M2 source → M1 drain via RF

⇒ 1 inversion for (−) fb w/ shunt mixing

23.10 d) Shunt - series

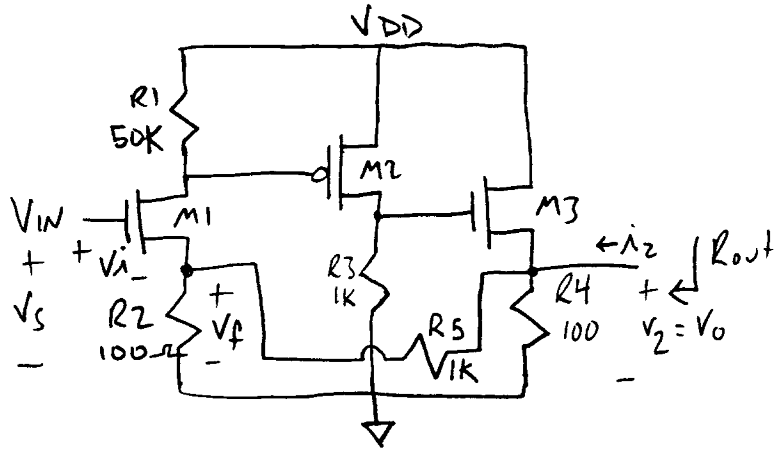


Fwd Path M1 gate - drain
M2 gate - drain

Fb Path M2 source → M1 gate via RF

1 inversion for (−) fb w/ shunt mixing

23.11

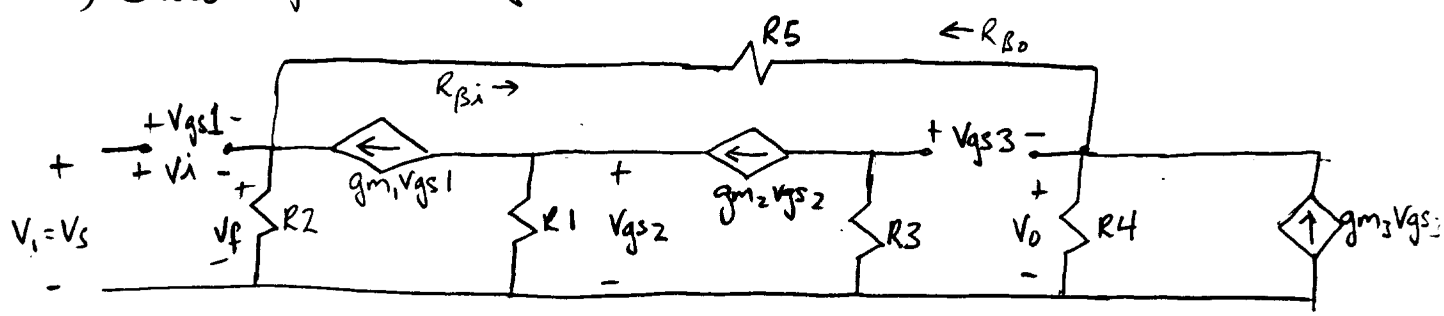


a) Series - Shunt since both input variables (V_i, V_f) and output variable (V_o) are voltages.

b) negative feeback since 2 inversions and series mixing

M1 gate → M1 drain = inv. #1
M2 gate → M2 drain = inv. #2
M3 gate → M3 source = <u>no inversion</u>

c) closed-loop small signal model

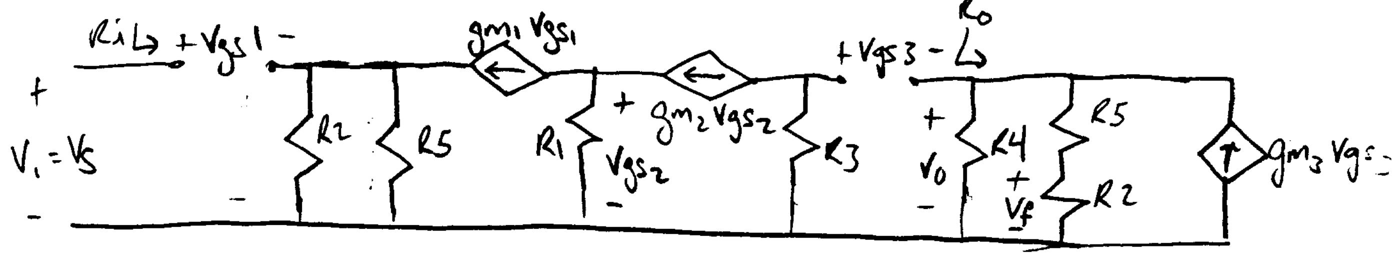


d) $R_{\beta i} = R_5$

$R_{\beta o} = R_5 + R_2$

23.12

a) small signal open loop model:



b) $$A_{OL}=\frac{V_o}{V_S}=\left(\frac{g_{m1}R_1}{g_{m1}(R_2||R_5)}\right)\left(g_{m2}R_3\right)\left(\frac{g_{m3}R_4||(R_2+R_5)}{g_{m3}R_4||(R_2+R_5)+1}\right)$$

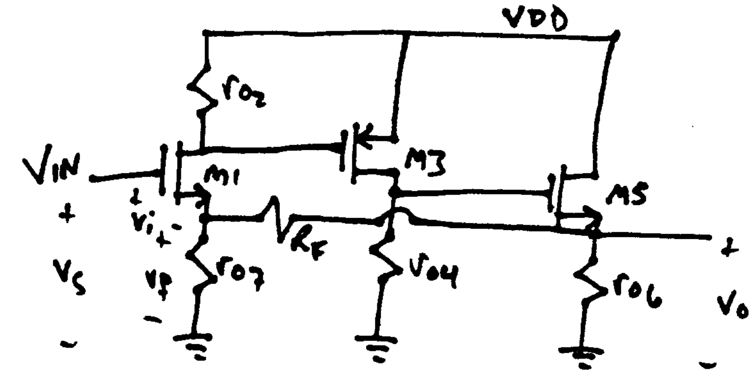
$$\beta=\frac{V_f}{V_o}=\frac{R_2}{R_2+R_5}$$

$$R_i=\infty$$
$$R_o=R_4||R_5+R_2$$

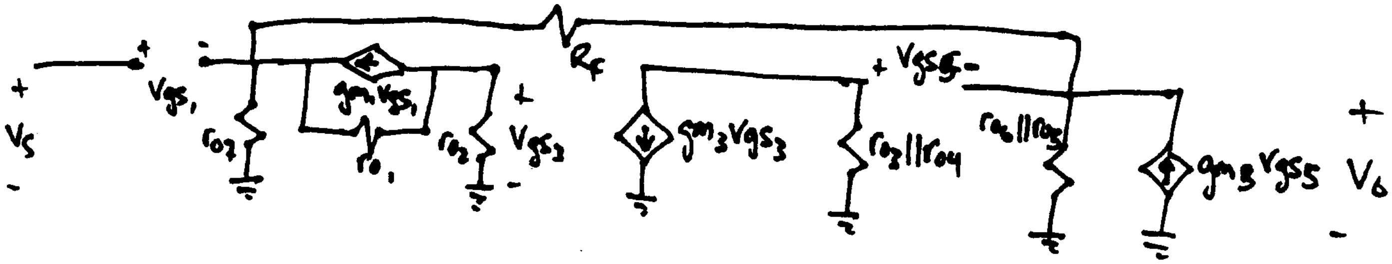
c) $$A_{CL}=\frac{A_{OL}}{1+A_{OL}\beta}$$

$$R_{out}=\frac{R_o}{1+A_{OL}\beta}$$

23.13 a)



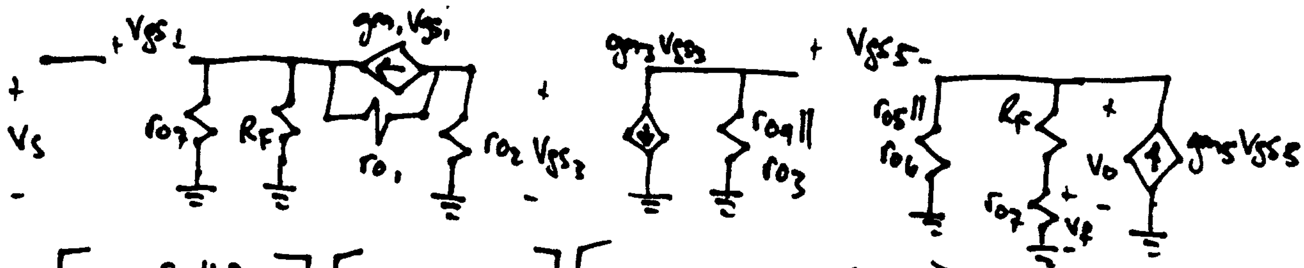
2 inversions ⇒ (−) fb !!



b) $R_{\beta i} = R_F = 10k\Omega$

$R_{\beta o} = R_F + r_{o7} = 80k\Omega$

23.14 a)



$$A_{OL} = \frac{V_o}{V_S} = \left[\frac{g_{m1}\, r_{o1}||r_{o2}}{g_{m1}\, r_{o7}||R_F + \underbrace{\cancel{1}}_{\approx 0}}\right]\left[g_{m3}\, r_{o4}||r_{o3}\right]\underbrace{\left[\frac{g_{m5}\, r_{o5}||r_{o6}||\cancel{R_F} + r_{o7}}{g_{m5}\, \cancel{r_{o5}||r_{o6}||R_F + r_{o7}} + 1}\right]}_{\approx 1} = 3.89k\ V/V$$

$$\beta = \frac{V_f}{V_o} = \frac{r_{o7}}{r_{o7}+R_F} = .875\ V/V$$

$R_i = \infty$ $\qquad R_o = r_{o5}||r_{o6}||(R_F + r_{o7}) = 29.17k||80k = 21.38\ k\Omega$

b) $$A_{CL} = \frac{A_{OL}}{1 + A_{OL}\beta} = 1.14\ V/V$$

$$R_{out} = \frac{R_o}{1 + A_{OL}\beta} = 6.28\Omega$$

23.15

$$A_{OL} = \left[\frac{g_{m1} r_{o1} \| r_{o2}}{g_{m1} R_1 \| R_F + 1}\right]\left[\frac{g_{m3} r_{o4}}{g_{m3} r_{o4} + 1}\right]\left[g_{m5}\left(\frac{1}{g_{m6}} \| r_{o6} \| r_{o8} \| (R_F + R_1)\right)\right]$$

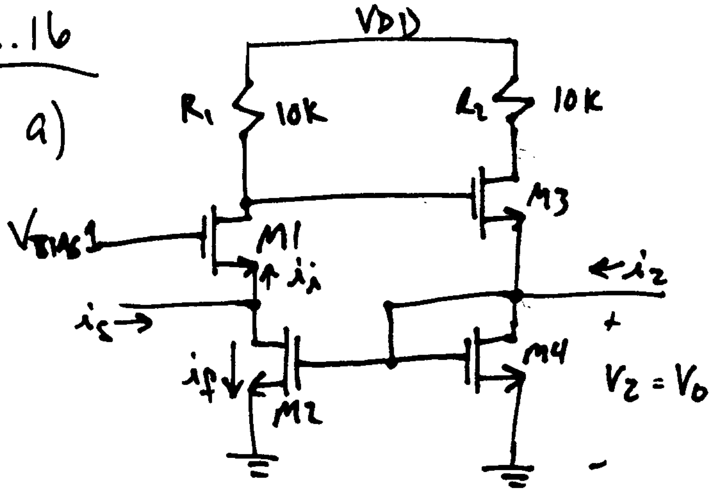
$$A_{OL} \simeq \left[\frac{g_{m1} r_{o1} \| r_{o2}}{g_{m1} R_1 \| R_F + 1}\right]\left[g_{m5}\left(\frac{1}{g_{m6}} \| (R_F + R_1)\right)\right] = 82.34 \text{ V/V}$$

$$\beta = \frac{V_F}{V_2} = \frac{R_1}{R_1 + R_2} = .5 \Rightarrow A_{CL} = \frac{V_2}{V_{IN}} = \frac{A_{OL}}{1 + A_{OL}\beta} = 1.952 \text{ V/V}$$

$$R_{out} = \frac{V_2}{i_2} = \frac{R_o}{1 + A_{OL}\beta} \simeq \frac{\frac{1}{g_{m6}} \| (R_F + R_1)}{1 + A_{OL}\beta} = .586\,\Omega = \frac{V}{A}$$

23.16

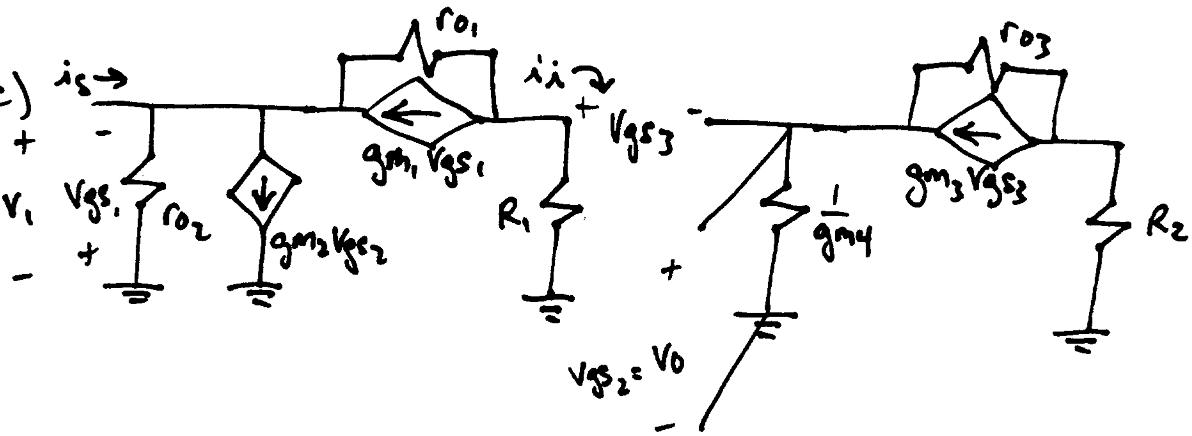
a)



Shunt-shunt

b) 1 inversions ⇒ (−) fb w/ shunt mixing

c)

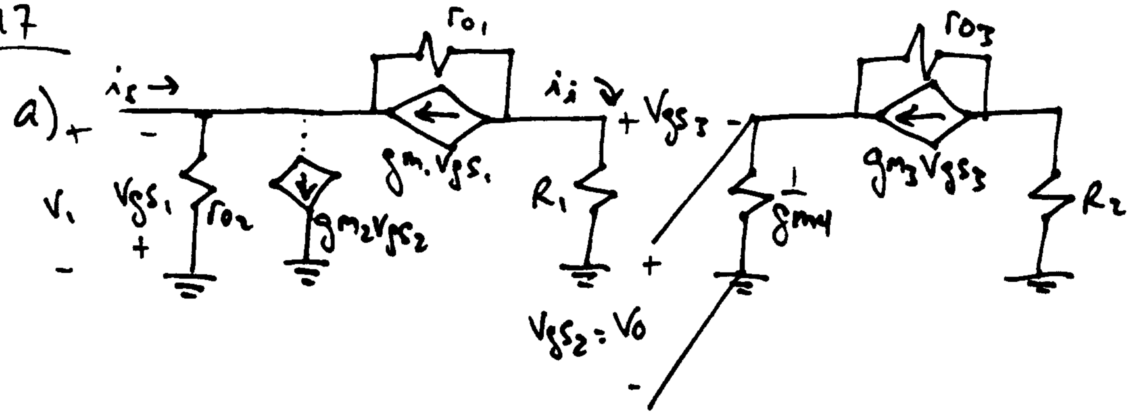


d) $R_{\beta o} = \infty = R_{inG4} || R_{inG2}$

$R_{\beta i} = r_{o2} = 70k\Omega$

23.17

a)



b) $\dfrac{V_o}{V_1} = [CG][CD] = \left[\dfrac{R_1}{r_{o2}}\right] \cdot \left[\dfrac{g_{m3} \cdot \frac{1}{g_{m4}}}{g_{m3} \cdot \frac{1}{g_{m4}} + 1}\right] = \left[\dfrac{1}{7}\right] \cdot \left[\dfrac{1}{2}\right] = \dfrac{1}{14} \approx .0714\ V/V$

$R_i = r_{o2} \| R_{INS_1} = r_{o2} \| \dfrac{1 + \frac{R_1}{r_{o1}}}{\frac{1}{r_{o1}} + g_{m1}} \approx \dfrac{1 + \frac{1}{7}}{\frac{1}{70k} + .06} = \boxed{19.04\,\Omega = R_i}$

$A_{OL} = \dfrac{V_o}{i_s} = \dfrac{V_o}{V_1} \cdot R_i = \left(\dfrac{1}{14}\right)(19.04) = \boxed{1.36\ V/A = A_{OL}}$

$\beta = \dfrac{i_f}{V_o} = \dfrac{g_{m2}V_{gs_2}}{V_{gs_2}} = g_{m2} = \boxed{.06\ A/V = \beta}$

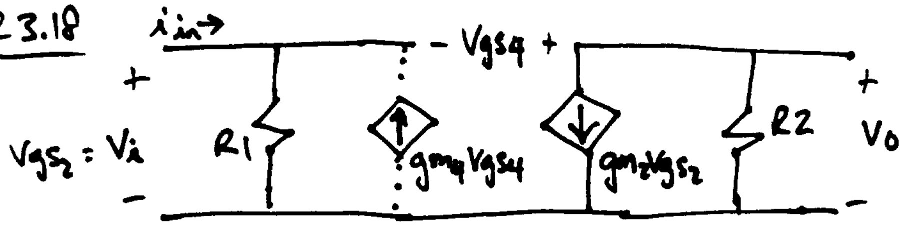
$R_o = \dfrac{1}{g_{m4}} \| R_{INS_2} = \dfrac{1}{g_{m4}} \| \dfrac{1 + \frac{R_2}{r_{o3}}}{\frac{1}{r_{o3}} + g_{m3}} = 16.67 \| 19.04 = \boxed{8.9\,\Omega = R_o}$

c) $A_{CL} = \dfrac{A_{OL}}{1 + A_{OL}\beta} = \dfrac{1.36\ A/V}{1 + 1.36(.06)} = \boxed{1.26\ A/V = A_{OL}}$

$R_{out} = \dfrac{R_o}{1 + A_{OL}\beta} = \dfrac{8.9}{1 + 1.36(.06)} = \boxed{8.23\,\Omega = R_{out}}$

$R_{IN} = \dfrac{R_i}{1 + A_{OL}\beta} = \dfrac{19.04}{1 + 1.36(.06)} = \boxed{17.6\,\Omega = R_{IN}}$

23.18



(open loop model)

$R_1 = \frac{1}{g_{m1}} \| r_{o1} \| r_{o4}$
$\approx \frac{1}{g_{m1}} = 16.67\,\Omega$

$R_2 = \frac{1}{g_{m3}} \| r_{o3} \| r_{o2}$
$\approx \frac{1}{g_{m3}} = 25\,\Omega$

$$A_{OL} = \frac{V_o}{V_i} \cdot R_1 = \frac{V_o}{i_{in}} = -g_{m2} \cdot R_2 \cdot R_1 = -25 \ \frac{V}{A}$$

$$\beta = \frac{i_f}{V_o} \approx \frac{-g_{m4}}{1 + g_{m4} R_1} = -.03 \ A/V \Rightarrow A_{CL} = \frac{V_2}{i_1} = \frac{A_{OL}}{1 + A_{OL}\beta} = \boxed{-14.3 \ V/A = \frac{V_2}{i_1}}$$

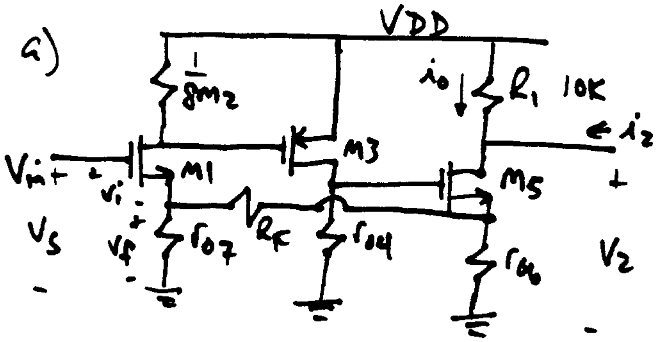
$$R_i = \frac{1}{g_{m1}} = 16.67\,\Omega, \quad R_{in} = \frac{V_1}{i_1} = \frac{R_i}{1 + A_{OL}\beta} = \boxed{9.5\,\Omega = \frac{V_1}{i_1}}$$

$$R_o = \frac{1}{g_{m3}} = 25\,\Omega, \quad R_{out} = \frac{V_2}{i_2} = \frac{R_o}{1 + A_{OL}\beta} = \boxed{14.3\,\Omega = \frac{V_2}{i_2}}$$

$$\frac{V_2}{V_1} = \frac{V_2}{i_1} \cdot \frac{i_1}{V_1} = A_{CL} \cdot \frac{1}{R_{in}} = \boxed{-1.5 \ V/V = \frac{V_2}{V_1}}$$

23.19

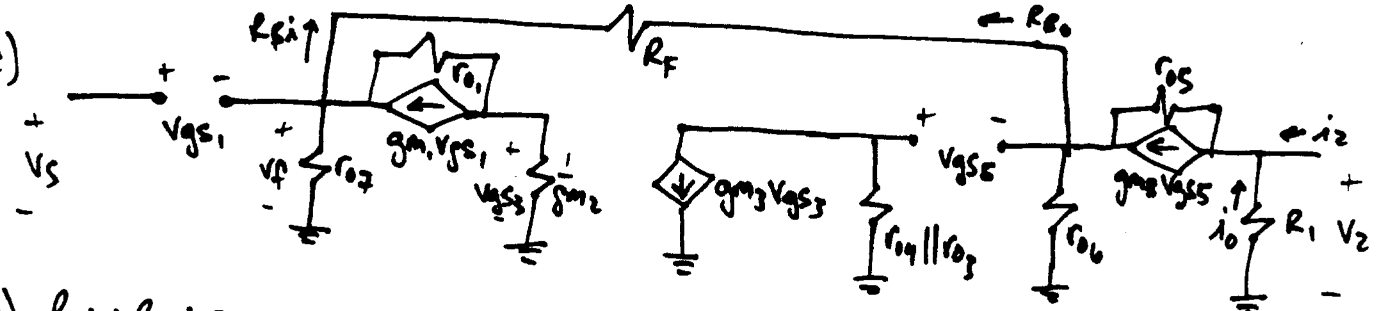
a)



Series-Series

b) 2 inversions ⇒ (−) fb w/ series mixing

c)

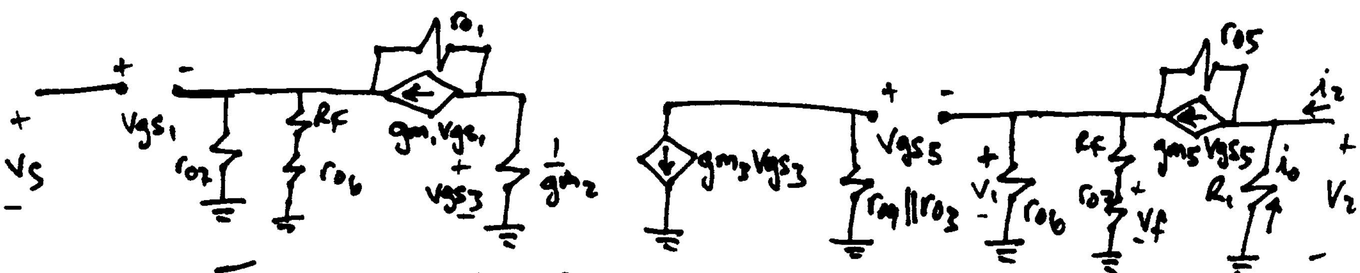


d) $R_{fi} = R_F + r_{o6} = 120k\Omega$

$R_{fo} = R_F + r_{o7} = 120k\Omega$

23.20

a)



b) $A_{OL} = \frac{i_o}{v_s} = \frac{-v_2}{v_s}\cdot\frac{1}{R_1} = \left[\frac{g_{m1}(r_{o1}\|\frac{1}{g_{m2}})}{g_{m1}(r_{o7}\|(R_F+r_{o6}))+1}\right]\left[g_{m3}\, r_{o3}\|r_{o4}\right]\left[\frac{g_{m5}}{g_{m5}(r_{o6}\|R_F+r_{o7})+1}\right] = 14.924\times10^{-6}\ A/V$

$\beta = \frac{v_f}{i_o} = \left(\frac{r_{o7}}{r_{o7}+R_F}\right)\left(\frac{r_{o6}(r_{o7}+R_F)}{r_{o6}+r_{o7}+R_F}\right) = \frac{r_{o7}\, r_{o6}}{r_{o6}+r_{o7}+R_{F}} = 25.789K\ V/A$

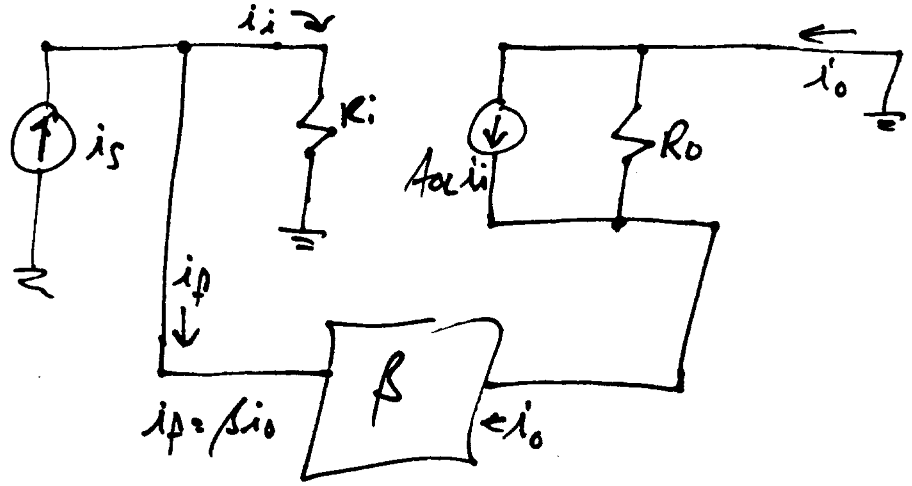
$R_i = \infty$ $\qquad R_o = R_1 + \overbrace{(r_{o6}\|R_F+r_{o7})}^{R_S} \overset{+\,r_o}{(r_{o5})}\overbrace{(1+g_{m5}\, r_{o6}\|R_F+r_{o7})}^{1+g_m R_S} = 186\ MEG\ \Omega$

c) $A_{CL} = \frac{A_{OL}}{1+A_{OL}\beta} = 10.776\times10^{-6}\ A/V$

$R_{in} = \infty$

$R_{out} = R_1\|(R_o - R_1) = 10k\|186MEG - 10k \approx R_1 = 10K$

23.21 find expressions for A_{CL}, R_{in}, and R_{out}

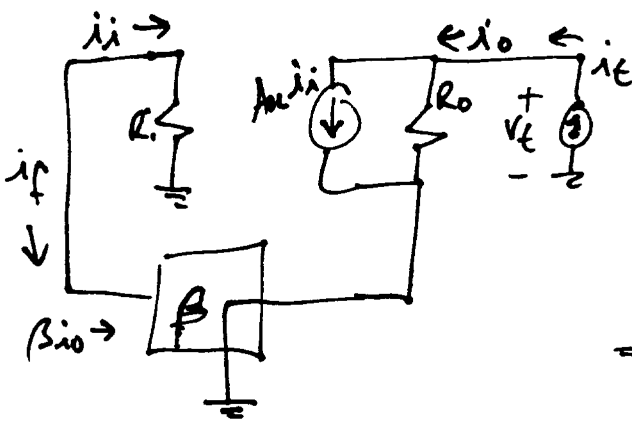


$$A_{CL} = \frac{i_o}{i_s} = \frac{i_o}{i_i + i_f} = \frac{i_o}{i_i + \beta i_o} = \frac{i_i \cdot A_{OL}}{i_i\left(1 + \frac{i_o}{i_i}\beta\right)} \quad \{\text{assuming } R_O = \infty\}$$

$$\Rightarrow \boxed{A_{CL} = \frac{A_{OL}}{1 + A_{OL}\beta}}$$

$$i_s = i_i + i_f = \frac{V_s}{R_i} + \beta i_o = \frac{V_s}{R_i} + \beta A_{OL} i_i \quad \{\text{again, if } R_O = \infty\}$$

$$i_s = \frac{V_s}{R_i}\left(1 + A_{OL}\beta\right) \Rightarrow \boxed{R_{in} = \frac{V_s}{i_s} = \frac{R_i}{1 + A_{OL}\beta}}$$

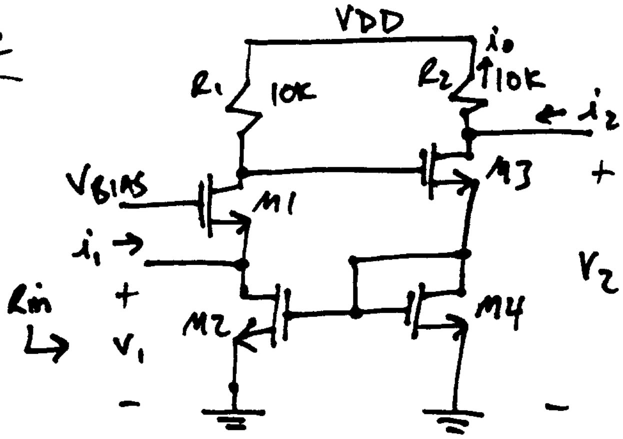


$$i_o = A_{OL} i_i + \frac{V_t}{R_O} = -A_{OL} i_f + \frac{V_t}{R_O} = -A_{OL}\beta i_o + \frac{V_t}{R_O}$$

$$\Rightarrow i_o\left(1 + A_{OL}\beta\right) = \frac{V_t}{R_O}$$

$$\Rightarrow \boxed{\frac{V_t}{i_o} = R_{out} = R_O\left(1 + A_{OL}\beta\right)}$$

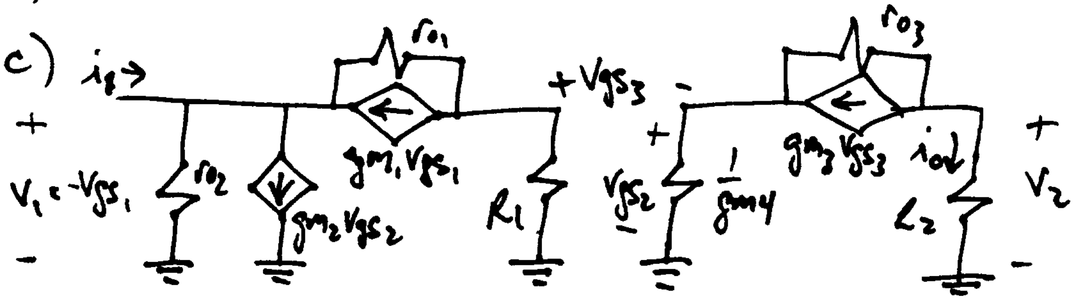
23.22



a) Shunt - series

b) 1 inversion ⇒ (-) fb w/ shunt mixing

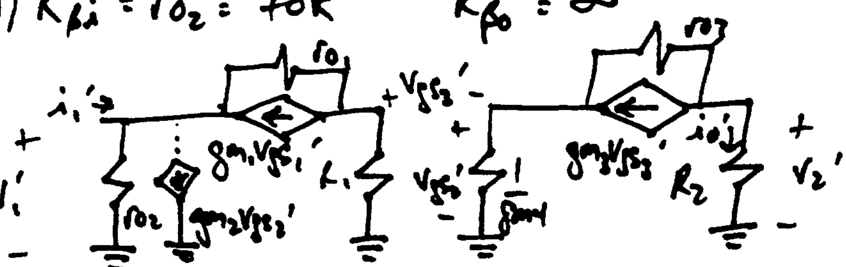
c)



d) $R_{\beta i} = r_{o2} = 70K \qquad R_{\beta o} = \infty$

23.23

a)



b) $\beta = \frac{i_f}{i_o} = \frac{g_{m2}V_{gs2}'}{-V_{gs2}' \cdot \left(\frac{1}{g_{m4}}\right)^{-1}} = \frac{-g_{m2}}{g_{m4}} = \boxed{-1 \text{ A/A} = \beta}$

~~Ri = ro2 = 70k = Ri Ro~~: $R_i = R_{IND2} \| R_{INS1} = \underline{19.04\Omega = R_i}$

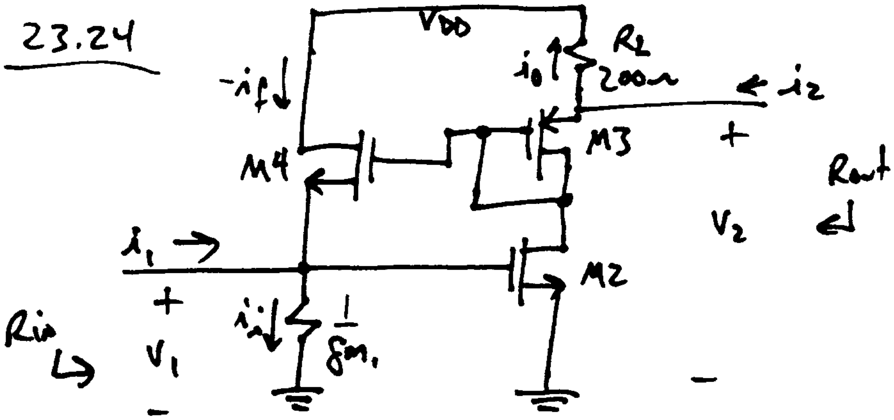
$R_o = R_2 + R_{IND3} = R_2 + \frac{1}{g_{m4}} + r_{o3}\left(1 + \frac{g_{m3}}{g_{m4}}\right) \approx R_2 + 2 \cdot r_{o3} = \underline{150k = R_o}$

$A_{OL} = \frac{i_o'}{i_s'} = \frac{v_o'}{v_s'} \cdot \frac{R_i}{R_2} = (CG)(CS)\frac{R_i}{R_2} = \left(\frac{R_1}{r_{o2}}\right)\left(\frac{-g_{m3} R_2 \| r_{o3}}{g_{m3}/g_{m4} + 1}\right)\left(\frac{R_i}{R_2}\right) = \boxed{-.0714 \text{ A/A} = A_{OL}}$

c) $A_{CL} = \frac{A_{OL}}{1 + A_{OL}\beta} = \boxed{.06664 \text{ A/V} = A_{CL}}$

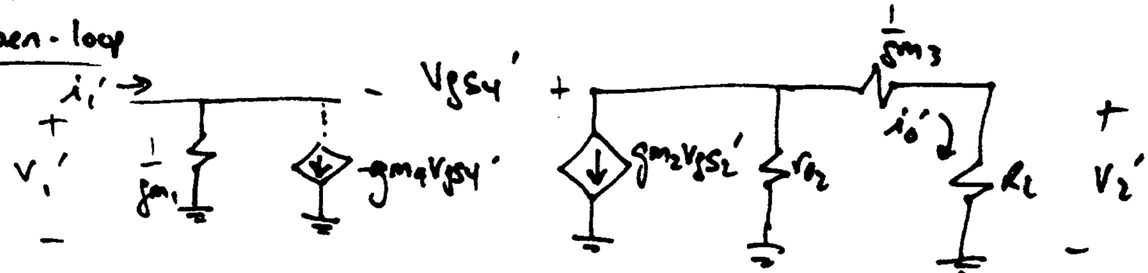
$R_{in} = \frac{R_i}{1 + A_{OL}\beta} = \boxed{18.7\Omega = R_{in}} \qquad R_{out} = R_2 \| \left[R_o(1 + A_{OL}\beta) - R_2\right] \approx R_2 = \boxed{10k\Omega = R_{out}}$

23.24



Shunt-series

Open-loop



$$R_i = \frac{1}{g_{m1}} \| \frac{1}{g_{m4}} = 8.34\,\Omega \qquad R_o = R_L \| \frac{1}{g_{m3}} + r_{o2} \approx R_L = 200\,\Omega$$

$$A_{OL} = \frac{i_o'}{i_1'} = \frac{V_2'}{V_1'} \cdot \frac{R_i}{R_O} = \frac{R_i}{R_O}\left[\frac{R_L}{R_L + \frac{1}{g_{m3}}}\right]\left[-g_{m2}\left(R_L + \frac{1}{g_{m3}}\right)\right] = \frac{8.34}{200} \cdot \frac{200}{216.67} \cdot -.06 \cdot 216.67 = -.5\,\frac{A}{A}$$

$$\beta = \frac{i_f'}{i_o'} = \frac{-g_{m4}V_{gs4}}{V_{gs4}\left(1 + \frac{g_{m4}}{g_{m1}}\right)} \cdot \left(R_L + g_{m1}\right) = -6.5\ A/A$$

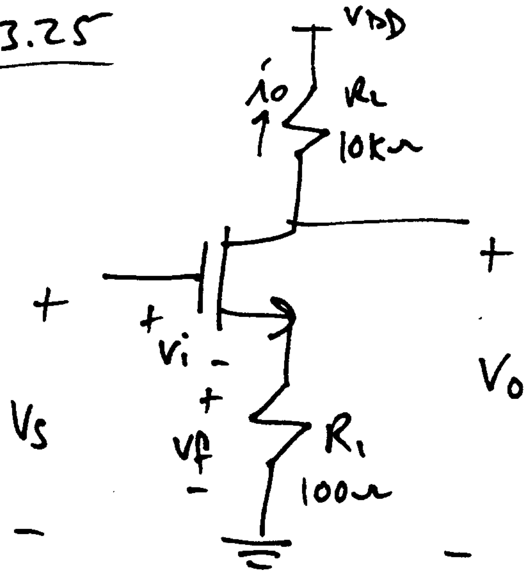
$$\Rightarrow R_{in} = \frac{R_i}{1 + A_{OL}\beta} = \frac{8.34\,\Omega}{1 + .5(6.5)} = \boxed{1.96\,\Omega = R_{in}}$$

$$R_{out} = R_L \| (R_{of} - R_L) = R_L \| \left(R_o(1 + A_{OL}\beta) - R_L\right) = 200 \| (650) = \boxed{153\,\Omega = R_{out}}$$

$$A_{CL} = \frac{i_2}{i_1} = \frac{A_{OL}}{1 + A_{OL}\beta} = \frac{-.5\ A/A}{4.25} = -.118\ A/A$$

$$\frac{V_2}{V_1} = \frac{i_2}{i_1} \cdot \frac{R_{out}}{R_{in}} = (-.118)\left(\frac{153}{1.96}\right) = \boxed{-9.2\ V/V = \frac{V_2}{V_1}}$$

23.25



Series-Series feed-back !!

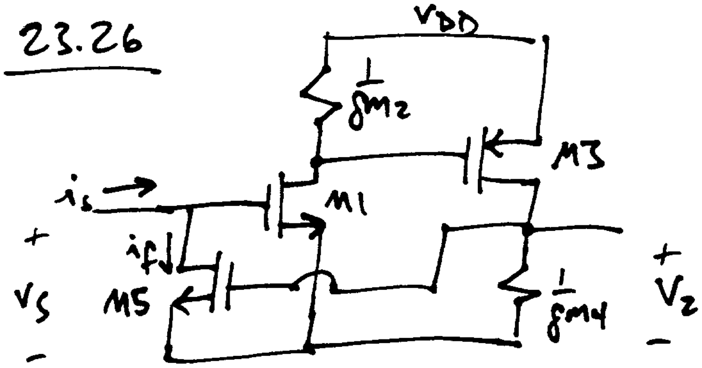
In words, any increase in Vs causes an increase in Vo. As Vo gets larger, the AC current through RL gets larger which is also flowing through R1. This increased current through R1 raises Vf, therefore causing the feedback.

$$A_{OL} = \frac{i_o}{v_s} = \frac{v_o}{v_s} \cdot \frac{1}{R_L} = [CS] \cdot \frac{1}{R_L} = \frac{-g_{m1} \cdot r_{o1} \| R_L}{g_{m1} R_1 + 1} \cdot \frac{1}{R_L} = \frac{-(.06) \cdot 70k \| 10k}{61} \cdot \frac{1}{10k}$$

$$\Rightarrow \boxed{A_{OL} = -860.7 \times 10^{-6}\ A/V}$$

$$\beta = \frac{v_f}{i_o} = \frac{-i_o \cdot R_1}{i_o} = -R_1 \quad \Rightarrow \boxed{\beta = -100\ V/A}$$

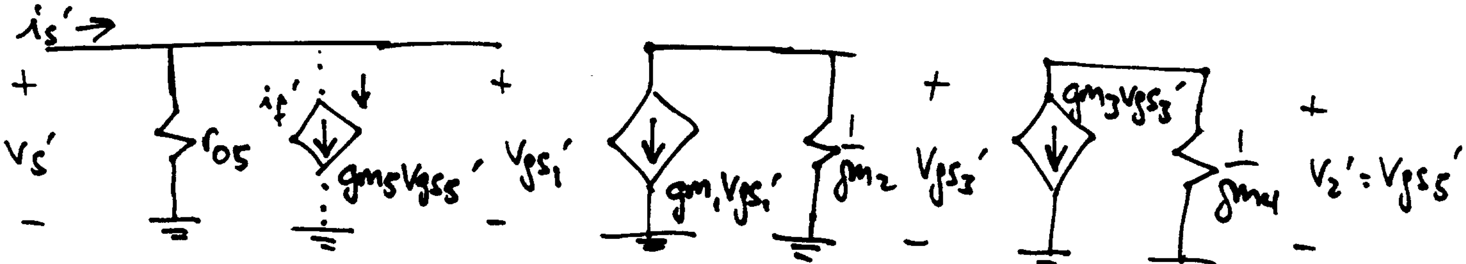
23.26



Shunt-shunt fb!

3 inversions for (−) fb w/ shunt mixing

$R_{\beta o} = \infty \qquad R_{\beta i} = R_{IN\,D5} = r_{o5}$



$R_i = r_{o5}$; $R_o = \frac{1}{g_{m4}}$; $\frac{v_2'}{v_1'} = (CS)(CS) = \left(-\frac{g_{m1}}{g_{m2}}\right)\left(-\frac{g_{m3}}{g_{m4}}\right) = 1\ V/V$

$$A_{OL} = \frac{v_2'}{i_s'} = \frac{v_2'}{v_1'} \cdot R_i = 1 \cdot r_{o5} \Rightarrow A_{OL} = 70k\ V/A$$

$$\beta = \frac{i_f'}{v_2'} = \frac{g_{m5} \cdot v_{gs5}'}{v_{gs5}'} = g_{m5} \Rightarrow \beta = .06\ A/V$$

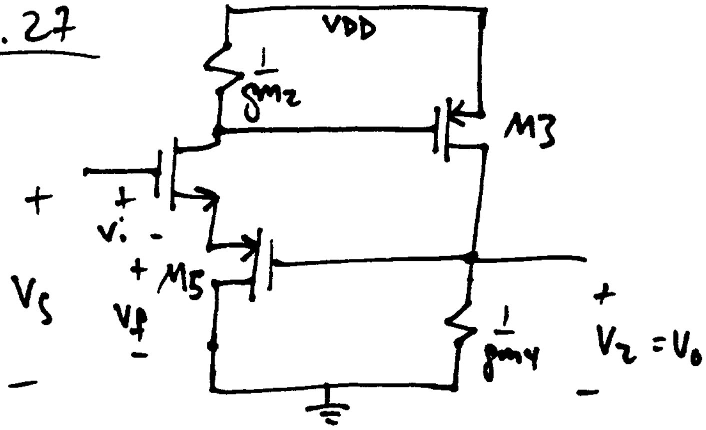
$\Rightarrow 1 + A_{OL}\beta = 4{,}201 \approx A_{OL}\beta = 4200$

$R_{in} = R_{if} = \frac{R_i}{1+A_{OL}\beta} \Rightarrow \boxed{R_{in} = 16.7\,\Omega} \qquad R_{out} = R_{of} = \frac{R_o}{1+A_{OL}\beta} = \boxed{.004\,\Omega = R_{out}}$

$$A_{CL} = \frac{A_{OL}}{1+A_{OL}\beta} = 16.7\ V/A = \frac{v_2}{i_s}$$

$$\Rightarrow \frac{v_2}{v_1} = \frac{v_2}{i_s} \cdot \frac{1}{R_{in}} = \frac{16.7\ V/A}{16.7\,\Omega} \Rightarrow \boxed{\frac{v_2}{v_1} = 1\ V/V}$$

23.27



Series-Shunt

2 inversions ⇒ (−) fb.

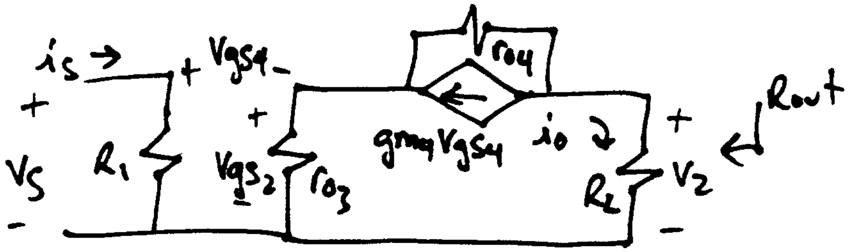
$$A_{OL} = \frac{V_2'}{V_S'} = [CS]\cdot[CS] = \left[\frac{-\frac{g_{m1}}{g_{m2}}}{1+g_{m1}r_{o5}}\right]\cdot\left[\frac{-g_{m3}}{g_{m4}}\right] = 333\times10^{-6}\ V/V$$

$$\beta = \frac{V_f'}{V_2'} = \frac{V_{gs5}'}{g_{m5}V_{gs5}'\cdot r_{o5}} = \frac{1}{g_{m5}\cdot r_{o5}} = 500\times10^{-6}\ V/V$$

$$\Rightarrow A_{CL} = \frac{A_{OL}}{1+A_{OL}\beta} = \frac{V_2}{V_1} = \boxed{333\times10^{-6}\ V/V = \frac{V_2}{V_1}}$$

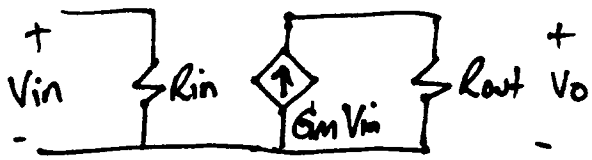
$$R_o \approx \frac{1}{g_{m4}} = 16.67\,\Omega \quad\Rightarrow R_{out} = \frac{R_o}{1+A_{OL}\beta} = \boxed{16.67\,\Omega = R_{out}}$$

23.28



$$A_{OL} = \frac{i_o}{i_S} = \frac{V_2}{V_S} \cdot \frac{R_1}{R_L}$$

$$\Downarrow$$



$$\frac{V_2}{V_S} = \frac{V_o}{V_{in}} = G_M R_{out}$$

$$G_M \triangleq \left.\frac{i_o}{V_{in}}\right|_{V_2=0}$$

$$R_{out} = R_L \| R_{IN,D4} = R_L \| \left(r_{o3} + r_{o4}(1 + g_{m4} r_{o3})\right)$$

w/ $V_2 = 0$

① $V_{gs2} = -i_o r_{o3}$ ② $\dfrac{V_{gs2}}{r_{o3}} = g_{m4} V_{gs4} - \dfrac{V_{gs2}}{r_{o4}}$

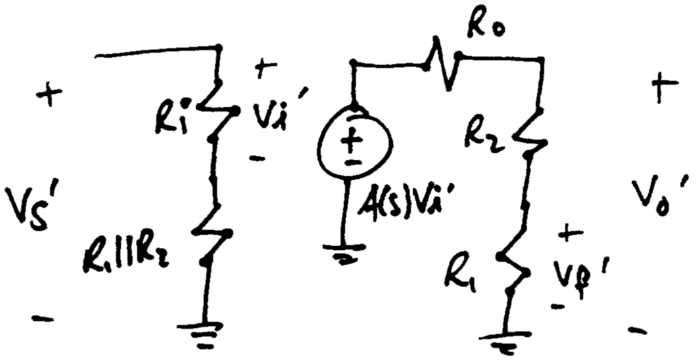
①→②: $-i_o = g_{m4} V_{gs4} + i_o \dfrac{r_{o3}}{r_{o4}} \Rightarrow \dfrac{i_o}{V_{gs4}} = \dfrac{-g_{m4}}{1 + \frac{r_{o3}}{r_{o4}}}$

and $\dfrac{V_{gs4}}{V_{in}} = \dfrac{1 + r_{o3}/r_{o4}}{1 + \frac{r_{o3}}{r_{o4}} + g_{m4} r_{o3}} \Rightarrow G_M = \dfrac{i_o}{V_{in}} = \dfrac{i_o}{V_{gs4}} \cdot \dfrac{V_{gs4}}{V_{in}} = \dfrac{-g_{m4}}{1 + \frac{r_{o3}}{r_{o4}} + g_{m4} r_{o3}}$

$$\Rightarrow A_{OL} = \frac{i_o}{i_S} = \frac{V_2}{V_S} \cdot \frac{R_1}{R_L} = G_M R_{out} \cdot \frac{R_1}{R_2} = \frac{-g_{m4} \cdot R_L \| \left(r_{o3} + r_{o4}(1 + g_{m4} r_{o3})\right)}{1 + \frac{r_{o3}}{r_{o4}} + g_{m4} r_{o3}}$$

23.29

Closed - loop



$$A(s) = \frac{100{,}000}{\left(\frac{s}{200}+1\right)^3}$$

R_i : 10 MΩ

R_o : 100 Ω

$R_1 = R_2 = 10$ KΩ

$$A_{OL} = \frac{V_o'}{V_s'} = A(s)\cdot\left[\frac{R_2+R_1}{R_2+R_1+R_o}\right]\cdot\left[\frac{R_i}{R_i+R_1\|R_2}\right] = \frac{\cancel{994{,}528}\ 99{,}453}{\left(\frac{s}{200}+1\right)^3}$$

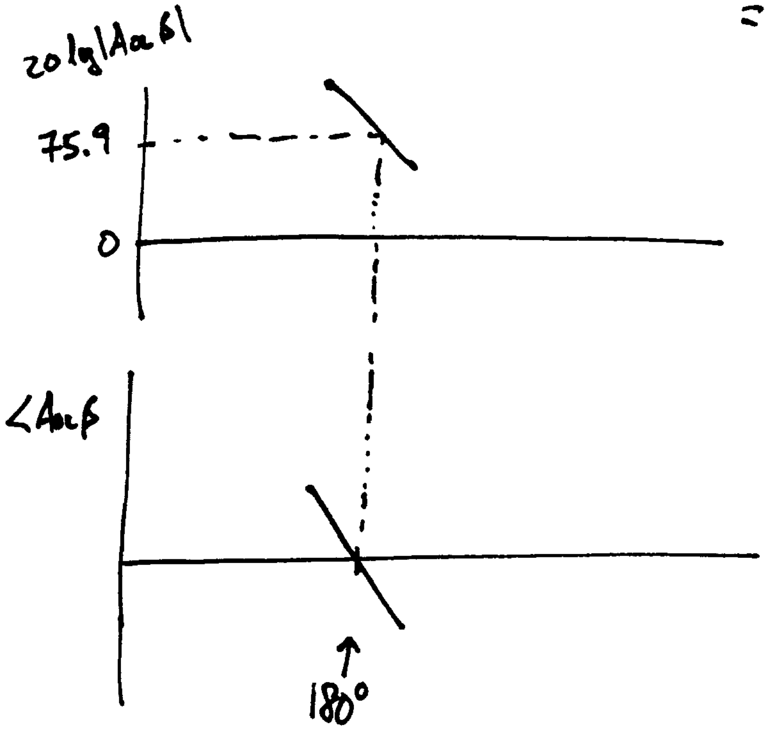
$$\beta = \frac{R_1}{R_1+R_2} = .5 \Rightarrow \text{loop gain} = A_{OL}(s)\beta = \frac{49{,}726}{\left(\frac{s}{200}+1\right)^3}$$

find ω_{180} : $-3\tan^{-1}\left(\frac{\omega_{180}}{200}\right) = -180 \Rightarrow \omega_{180} = 200\tan(60) = 346.41$ r/s

find $|A_{OL}(j\omega)\beta|$, dB @ $\omega = \omega_{180}$: $\Rightarrow 20\log(49{,}726) - 3\left(20\log\sqrt{\left(\frac{346.41}{200}\right)^2+1}\right)$

$= 75.87$ dB > 0 dB

$\Rightarrow$ unstable



23.30

$$A_{OL}(j\omega) = \frac{10{,}000}{\left(1+\frac{j\omega}{100}\right)\left(1+\frac{j\omega}{\omega_2}\right)} = A_{ol}(j\omega)\cdot\beta, \quad \text{since } \beta = 1$$

finding ω_{0dB}:

$$1 = \frac{10{,}000}{\sqrt{\left(1+\left(\frac{\omega_{0dB}}{100}\right)^2\right)\left(1+\left(\frac{\omega_{0dB}}{\omega_2}\right)^2\right)}} \Rightarrow \left(1+\left(\frac{\omega_{0dB}}{100}\right)^2\right)\left(1+\left(\frac{\omega_{0dB}}{\omega_2}\right)^2\right) = 10{,}000^2$$

$$\Rightarrow \frac{\omega_{0dB}^4}{100^2\cdot\omega_2^2} + \omega_0^2\left(\frac{1}{100^2}+\frac{1}{\omega_2^2}\right) - 100\times10^6 = 0$$

$$\Rightarrow \quad \omega_{0dB} \simeq \sqrt{\left(\sqrt{\left(\frac{1}{100}\right)^4 + \frac{40{,}000}{\omega_2^2}} - \left(\frac{1}{100}\right)^2\right)\cdot\left(5{,}000\cdot\omega_2^2\right)} = \text{EQN 1}$$

finding phase margin

$$PM = \phi_m = \operatorname{Arg}\left(A(j\omega)\beta\right)\Big|_{\omega=\omega_{0dB}} - (-180^\circ)$$

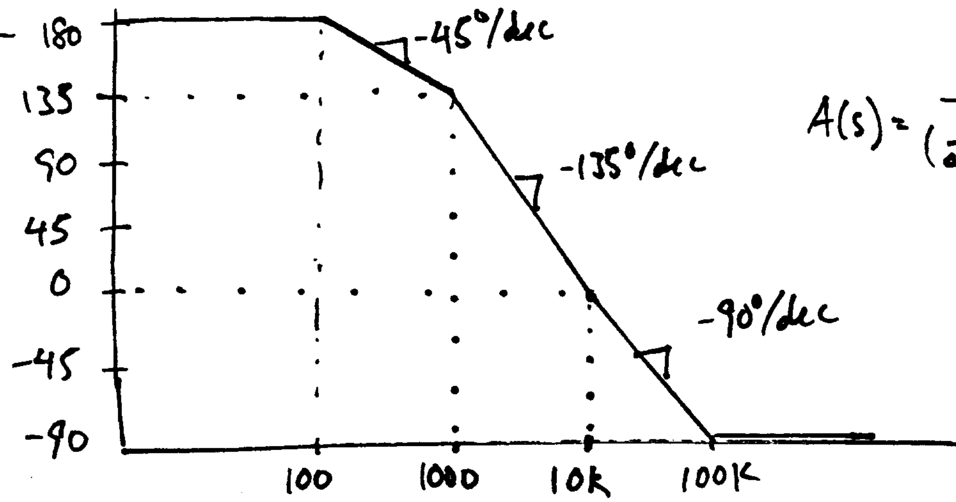
$$\Rightarrow \phi_m = -\tan^{-1}\left(\frac{\omega_{0dB}}{100}\right) - \tan^{-1}\left(\frac{\omega_{0dB}}{\omega_2}\right) + 180^\circ$$

and since 100 r/s is relatively small...

$$\phi_m \simeq 90^\circ - \tan^{-1}\left(\frac{\omega_{0dB}}{\omega_2}\right) = \text{EQN 2}$$

ω_2 (given)	ω_{0dB} (EQN 1)	ϕ_m (EQN 2)	Stable?
10^5 r/s	308 k r/s	17.6°	yes
10^6 r/s	786 k r/s	51.83°	yes
10^7 r/s	995 k r/s	84.3°	yes
5×10^6 r/s	981.3 k r/s	78.9°	yes

23.31



$$A(s) = \frac{-1000}{\left(\frac{s}{\omega_1}+1\right)\left(\frac{s}{\omega_2}+1\right)\left(\frac{s}{\omega_3}+1\right)}$$

$$\left.\begin{aligned} \omega_1 &= 1000 \\ \omega_2 &= 10K \\ \omega_3 &= 10K \end{aligned}\right\} \text{from given slopes}$$

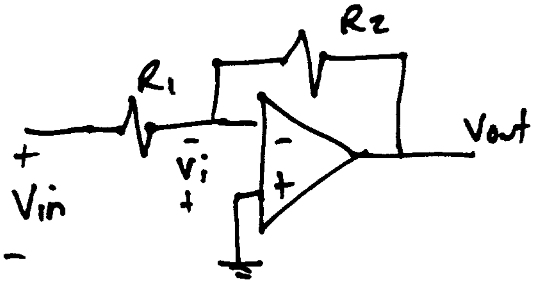
also, $\omega_{180} = 10K$

$$A(s) = \frac{-1000}{\left(\frac{s}{1000}+1\right)\left(\frac{s}{10K}+1\right)^2}$$

$\Rightarrow$ set $|A(j\omega)\beta| = 1$ @ ω_{180}

$$\Rightarrow \frac{1000\beta}{\sqrt{\left(\frac{\omega_{180}}{1000}\right)^2+1}\left[\sqrt{\left(\frac{\omega_{180}}{10k}\right)^2+1}\right]^2} = 1 \quad \Rightarrow \boxed{\beta = .0201}$$

23.32

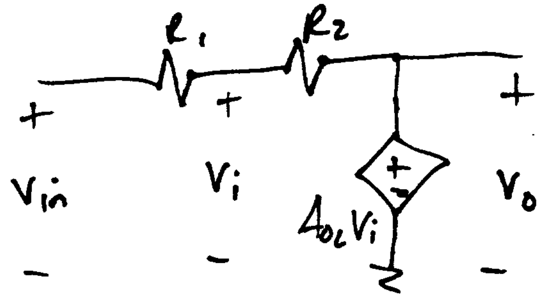


$R_1 = 1K\Omega$

$R_2 = 10K\Omega$

$\frac{V_{out}}{V_{in}} = -5\ V/V$

$\Downarrow$ model (assuming $R_i = \infty$, $R_o = 0$)



using superposition, $V_i = -V_{in} \cdot \frac{R_2}{R_1+R_2} - V_o \cdot \frac{R_1}{R_1+R_2}$

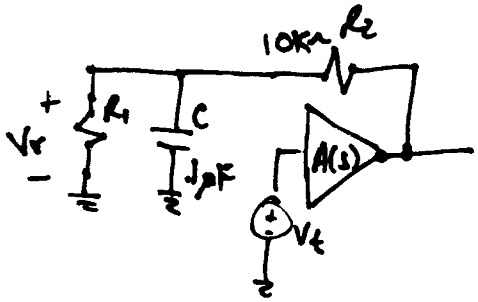
also, $V_i = \frac{V_{out}}{A_{OL}}$

$$\Rightarrow V_{out}\left(\frac{1}{A_{OL}} + \frac{R_1}{R_1+R_2}\right) = -V_{in} \cdot \frac{R_2}{R_1+R_2}$$

$$\Rightarrow \frac{V_{out}}{V_{in}} = \frac{-\frac{R_2}{R_1+R_2}}{\frac{1}{A_{OL}} + \frac{R_1}{R_2}} \Rightarrow \frac{1}{A_{OL}} = \frac{-\frac{R_2}{R_1+R_2}}{\frac{V_{out}}{V_{in}}} - \frac{R_1}{R_1+R_2}$$

$$\Rightarrow \frac{1}{A_{OL}} = \frac{-\frac{10}{11}}{-5} - \frac{1}{11} = .0\overline{909} \Rightarrow \boxed{A_{OL} = 11\ V/V}$$

23.33



$\omega_{0dB} = 8{,}000\ r/s$

$\phi_m = 45°$

$A(s) = \dfrac{-A_0}{\left(\frac{s}{200}+1\right)\left(\frac{s}{10k}+1\right)}$ find A_0 & R_1

$$\frac{V_r}{V_t} = A(s)\cdot\frac{\frac{1/C}{s+1/R_1C}}{\frac{1/C}{s+1/R_1C}+R_2} = \frac{A(s)}{R_2C}\cdot\frac{1}{s+\frac{1}{C}\left(\frac{1}{R_1}+\frac{1}{R_2}\right)} \Rightarrow \text{let } x = \frac{1}{R_1C}$$

$$\Rightarrow \frac{V_r}{V_t} = \frac{\left(\frac{1000}{1000+x}\right)A(s)}{\left(\frac{s}{1000+x}+1\right)} = \frac{-A_0\left(\frac{1000}{1000+x}\right)}{\left(\frac{s}{1000+x}+1\right)\left(\frac{s}{200}+1\right)\left(\frac{s}{10k}+1\right)} = -A(s)\beta(s)$$

$$\phi_m = \operatorname{Arg}(A(j\omega)\beta(j\omega))\Big|_{\omega=8k} + 180° = 45° \Rightarrow \operatorname{Arg}(A(j\omega)\beta(j\omega))\Big|_{\omega=8k} = -135°$$

$$\Rightarrow \tan^{-1}\left(\frac{8k}{1000+x}\right) + \tan^{-1}\left(\frac{8k}{200}\right) + \tan^{-1}\left(\frac{8k}{10k}\right) = 135°$$

$$\Rightarrow \tan^{-1}\left(\frac{8k}{1000+x}\right) = 7.772 \Rightarrow x = 57.6\,K$$

$$\Rightarrow \boxed{R_1 = 174\,\Omega}$$

$$|A(j\omega)\beta(j\omega)|\Big|_{\omega=8k} = 1 = \frac{A_0(.017)}{\sqrt{\frac{8k^2}{58.6k^2}+1}\sqrt{\frac{8k^2}{200^2}+1}\sqrt{\frac{8k^2}{10k^2}+1}}$$

$$\Rightarrow \boxed{A_0 = 3{,}042\ v/v}$$

23.34

$$RR = -\frac{V_r}{V_t} = A_{OL}(s)\beta(s) = \frac{49{,}726}{\left(\frac{s}{200}+1\right)^3}$$ is it stable?

first find ω_{180}: $-3\tan^{-1}\left(\frac{\omega_{180}}{200}\right) = -180°$

$$\Rightarrow \omega_{180} = 200 \cdot \tan(60°) = 346.41 \text{ r/s}$$

now find $$\left|A(j\omega)\beta(j\omega)\right|\Big|_{\omega=\omega_{180}} = 20\log(49{,}726) - 3\left(20\log\sqrt{\left(\frac{346.41}{200}\right)^2+1}\right)$$

$$= 75.87\text{ dB} > 0\text{ dB}$$

$\Rightarrow$ <u>unstable</u>