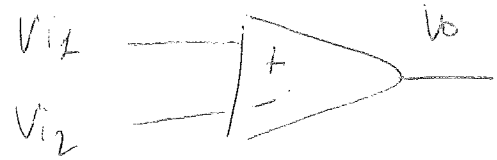
DIFFERENTIAL AMPLIFIER – CHAPTER 9

DIFF AMP. → similar to op-amp w/o feedback loop.



∘ advantages: diff mode gain

$\frac{V_o}{V_{i1} - V_{i2}}$ made very large (noise rejection)

∘ Common mode gain

$\frac{V_o}{\frac{1}{2}(V_{i1} + V_{i2})}$ made as close to 0.

→ Dominant configuration for amplifiers since active load resistances can be easily made.

A_d = Diff mode gain

V_d = Diff mode input $= V_{i1} - V_{i2}$

A_m = Common mode gain.

V_{cm} = Common mode input $= \underbrace{\frac{1}{2}(V_{i1} + V_{i2})}_{\text{average of 2 inputs}}$

V_o has 2 components

$$V_o = \underbrace{A_d \cdot V_d}_{\text{diff mode}} + \underbrace{A_{cm} \cdot V_{cm}}_{\text{common mode}}$$

Make $A_d \gg A_{cm}$

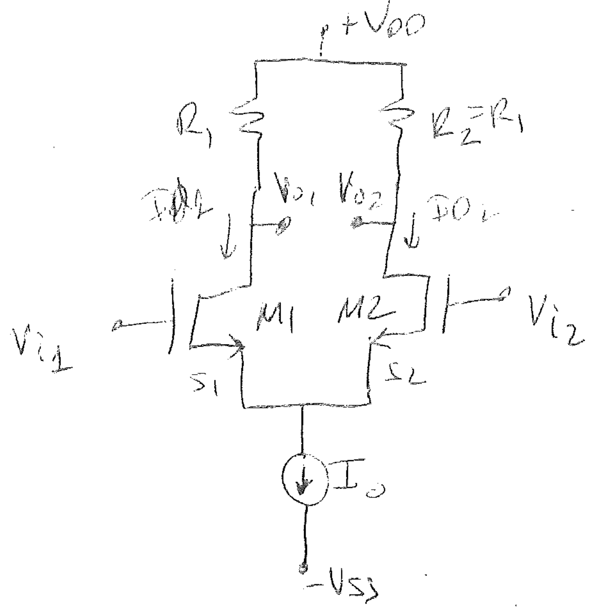
→ Ideal diff. amp. $A_{cm} \to 0$

→ Non-ideal diff. amp: Common mode rejection ratio. CMRR (in dB)

10/12/2016
(2)

$$CMRR = 20 \cdot \log\left(\frac{A_d}{A_{cm}}\right)$$ ~ typical >100 dB

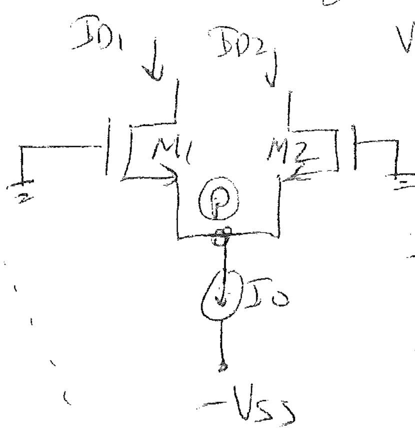
Circuit: Basic diff amp:
→ Source-coupled diff amp (w/ resistive load)



★ M_1, M_2 are identical
same K, V_T

★ DC analysis:
(No small signal $V_{i1} = V_{i2} = 0V$)

~~$V_{GS1} = V_{GS2}$~~
$V_{GS1} = V_{GS2}$
[no small signal]



$I_{D1} = I_{D2}$

$I_O = I_{D1} + I_{D2}$

$$\underbrace{I_{D1} = I_{D2} = \frac{I_O}{2}}_{\text{whether or not } R_1 = R_2}$$

★ small-signal analysis $\left(\begin{array}{l}(1) \to \text{diff mode} \\ (2) \to \text{common mode}\end{array}\right]$

(1) <u>Strictly diff mode operation:</u>
make $V_{i1} = -V_{i2}$ $\quad V_{i1} = \frac{1}{2}V_d$, $V_{i2} = -\frac{1}{2}V_d$

$V_d = V_{i1} - V_{i2}$

$$V_d = \frac{1}{2}V_d - \left(-\frac{1}{2}V_d\right) = V_d$$

If $V_d > 0$: I_{D1} will increase from its Q-point value by ΔI_{D1}

$$\left.\begin{array}{l} I_{D1} = \frac{1}{2}I_O + \Delta I_{D1} \\ I_{D2} = \frac{1}{2}I_O - \Delta I_{D2} \end{array}\right\}$$ I_{D2} will decrease from its Q-point value.

And $V_{O1} = V_{DD} - R_1 I_{D1}$

$V_{O2} = V_{DD} - R_1 I_{D2}$

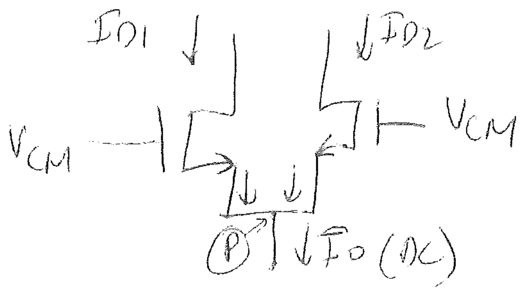
$V_{O1} - V_{O2} = -R_1(I_{D1} - I_{D2})$

$V_{O1} - V_{O2} = -R_1(2\Delta I_D)$

② Strictlly common mode input

$V_{i1} = V_{i2} = V_{CM}$

$V_{CM} = \frac{1}{2}(V_{i1} + V_{i2})$ ← make it average of both inputs..



$I_{D1} = \frac{1}{2} I_0 + \Delta I_{D1}$

$I_{D2} = \frac{1}{2} I_0 + \Delta I_{D1}$

$\Delta I_{D1} = \Delta I_{D2}$

At node Ⓟ $I_{D1} + I_{D2} = I_0$

$I_{D1} = \frac{1}{2} I_0 + \Delta I_{D1}$

$I_{D2} = \frac{1}{2} I_0 + \Delta I_{D1}$

$I_{D1} + I_{D2} = I_0 + 2\Delta I_{D1}$

But $I_{D1} + I_{D2} = I_0$

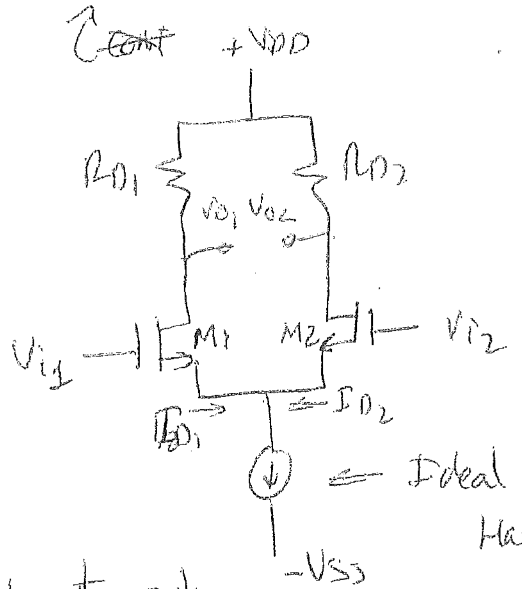
$\therefore \Delta I_{D1} = 0$ (only possible solution)

∴ No change in the outputs V_{o1} or V_{o2}

∴ $\boxed{\text{Common mode gain} = 0.}$ → Ideal diff. amp.

$A_{CM} = 0$

What happens when not ideal → Friday.



- M1, M2 : identical
- R_{D1} may not be equal to R_{D2}

← Ideal current source
Has $R_o = \infty$

How to solve:

① DC analysis (no signals), find Q-points.

$I_{D1} = I_{D2} = \frac{1}{2} I_o$ (regardless of R_{D1}, R_{D2} being equal)

Calculate V_{OS1} and V_{OS2} at Q-point.

Calculate g_m.

② Small-signal analysis

Find → ⓐ Differential mode gain A_d

$v_{i1} = -v_{i2} = \frac{1}{2} v_d$

Find ⓑ Common mode gain. A_{cm}

$v_{i1} = v_{i2} = v_{cm}$

For general input situation:

$V_o = A_d \cdot V_d + A_{cm} \cdot V_{cm}$

$V_d = V_{i1} - V_{i2}$

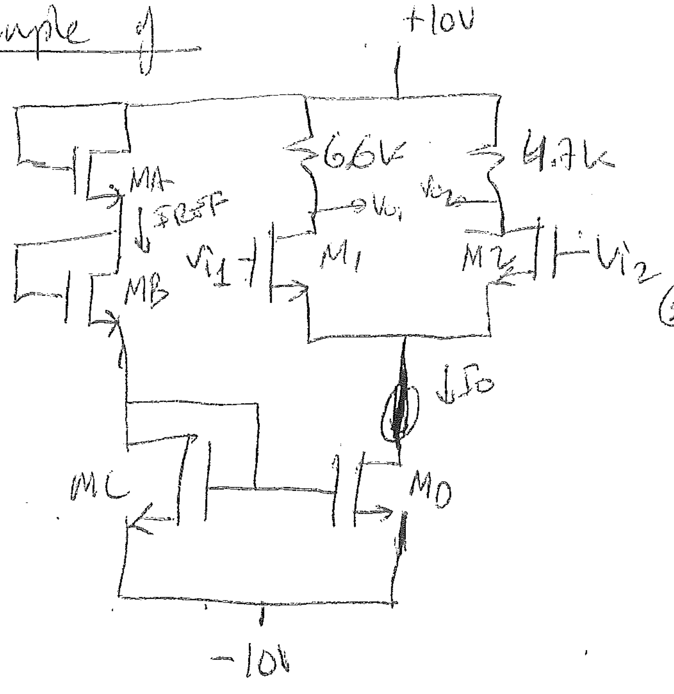
$V_{cm} = \frac{1}{2}(v_{i1} + v_{i2})$

Ideal diff. amp:

R_o of current source $\to \infty$

$\therefore A_{CM} = 0$

Example 4



$K = \cancel{1.8}\ 0.1\ mA/V^2$ } for all
$V_T = 0.8V$ } transistors

(*) MA, MB, MC, MD make up the current source
→ Basic current mirror with two additional transistors.

DC MA, MB, MC are identical and same current I_{REF} flows through them.
V_{GS} must be the same for MA, MB, MC.
Total voltage available: 20V, ∴ $V_{GS} = \frac{20V}{3} = 6.6\bar{7}V$

$$\therefore I_{REF} = \frac{1}{2}(\cancel{1.8}\ 0.1\ mA/V)(V_{GS} - 0.8)^2$$
$$V_{GS} \to 6.687$$

$I_{REF} = 1.72\ mA = I_o$

At Q-point (meaning that $v_{i1} = v_{i2} = 0$)

$$I_{D1} = I_{D2} = \frac{1.72 mA}{2} = 0.8605\ mA = \frac{I_o}{2} = \frac{I_{REF}}{2}$$

V_{GS1}:

$$0.8605 mA = \frac{1}{2}(0.1\ mA/V^2)(V_{GS1} - 0.8)^2$$

$V_{ov}^2 = \cancel{4.302}\ 17.21$

$V_{ov} = 4.14$

$V_{GS} - V_T = 4.14$

$V_{GS} = 4.94V$

$V_{GS1} = 4.948V$

And $g_{m1} = K(V_{GS} - V_T) = 0.1\ mA/V^2(4.948 - 0.8)$

$\boxed{g_{m1} = 0.4148\ mS}$

10/14/2016
(3)

→ Identify saturation operation of M_D.
(MA, MB, Mc always in sat.)

Want V_{GD} of $M_D < 0.8V$ $\qquad V_{DS_D} > (V_{GS_D} - V_T)$

→ V_{GS} of $M_D = V_{GS}$ of M_C

V_G of $M_D = -10 + V_{GS} = -10 + (6.667) = -3.33V$

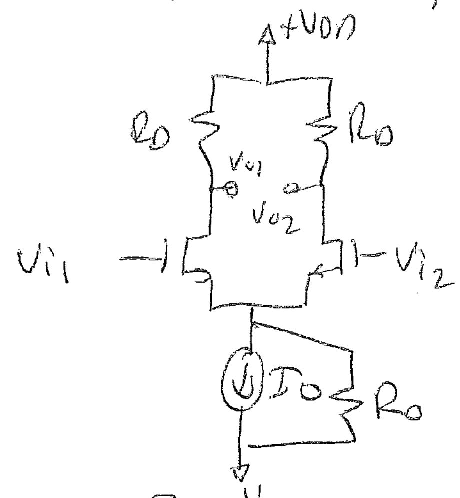
→ V_D of $M_D = 0 - V_{GS1} = 0 - 4.948V$ → ? $V_D = 4.948V$

V_{GD} of $M_D \leq 0.8V$ ⟶ ?

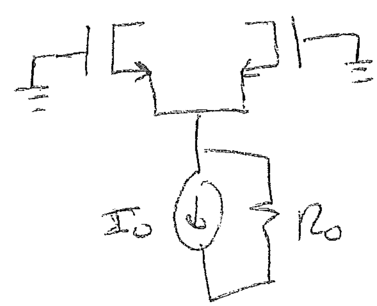
$V_{GD} = V_G - V_D = -3.33V - (-4.948V) = 1.61$

Small-signal analysis.

Q point $v_{i1} = v_{i2} = 0$



Non-ideal current source.



$I_{D1} + I_{D2} = I_O \cdot I_{R_O}$

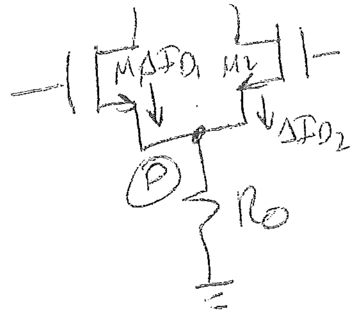
$I_{R_O} << I_O$

↳ Ignore I_{R_O} at Q-point

∴ $I_{D1} = I_{D2} = \frac{1}{2} I_O$ at Q-point

Diff. mode analysis

$V_{i1} - V_{i2} = V_d$

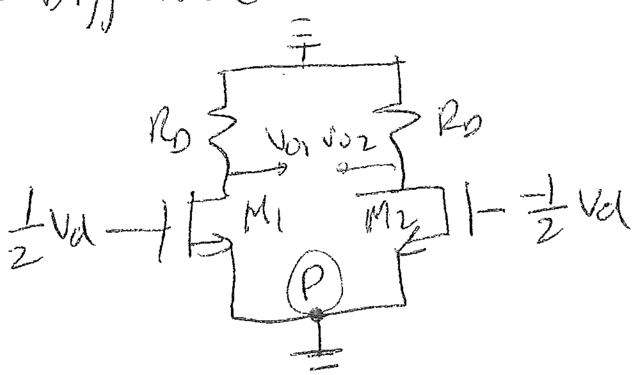


$\Delta I_{D1} = -\Delta I_2$ ∴ no current flows through R_o. $I_{R_o} \to 0$ for diff. mode.

→ Diff. mode → voltage at (P) is not affected since no current in R_o.

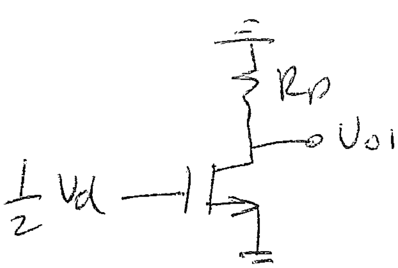
∴ (P) acts as an a.c. ground.

→ Diff. mode → ckt can be changed to:



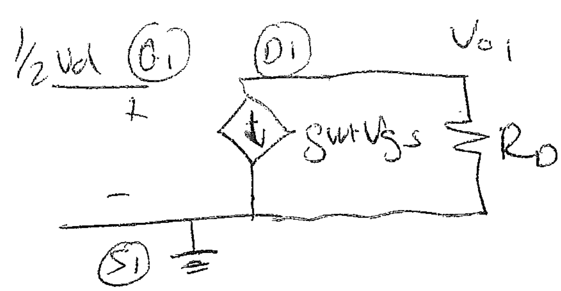
← two-halfs look the same. Only sign of input voltage is different.
Find output voltage of 1/2 half and change sign for other half.

→ One half of Diff. amp.



CS amplifier.

⟹ small signal model



$$\frac{V_{o1}}{V_{gs1}} = -g_{m1} R_D$$

$$\frac{V_{gs1}}{V_d} = \frac{1}{2}$$

10/14/2016

(4)

$$Ad\,(\text{single-ended}) = \frac{V_{O1}}{V_d} = -\frac{1}{2} g_m R_{D1}$$

Other half:

$$\frac{V_{O2}}{V_d} = \frac{1}{2} g_m R_{D2}$$

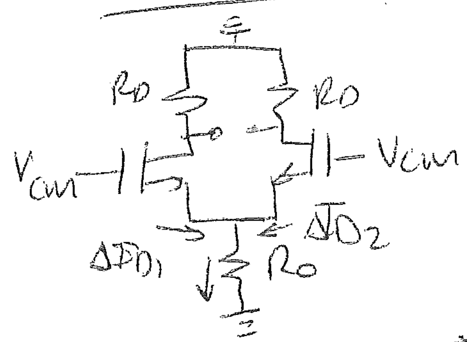
$$Ad\,(\text{double-ended}) = \frac{V_{O1} - V_{O2}}{V_d} = -g_m(R_{D1} - R_{D2})$$

$$Ad = -g_m(R_{D1} - R_{D2})$$

↑ double ended

END ↑

START ↓ Common-mode analysis

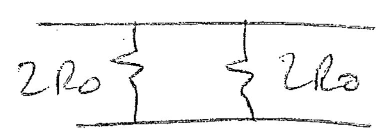


$\Delta I_{D1} = \Delta I_{D2}$

ΔI_{D1} + ΔI_{D2} same sign.

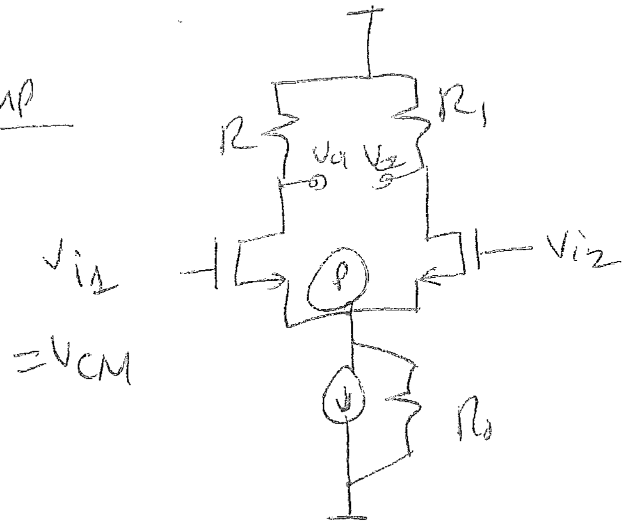
$\therefore \Delta I_{D1} + \Delta I_{D2} = I_{Ro} \neq 0$

→ Cannot cut ckt in half as is.
But Replace Ro with $\cancel{2}$(2Ro) and divide in 1/2.

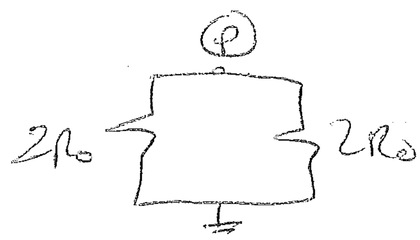


New lecture:

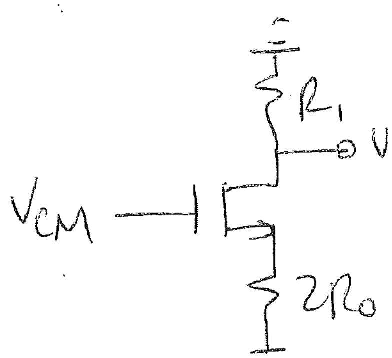
DIFF AMP



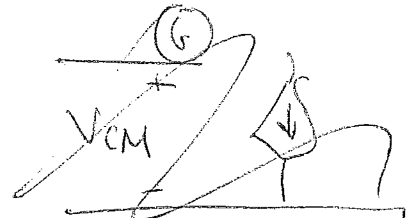
Common-mode analysis. I Source → open
V source → shorted.



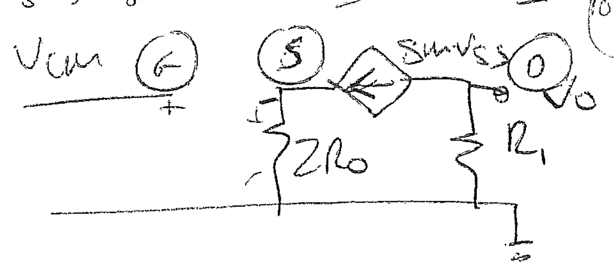
One-half diff amp:



⟹ small-signal



$V_s = g_m V_{gs} \cdot 2R_o$ S



$V_o = -g_m \ldots R$

$$\frac{V_o}{V_{gs}} = -g_m R_1$$

$$V_{gs} = V_{CM} - 2R_o(g_m V_{gs})$$

$$V_{gs}(1 + 2g_m R_o) = V_{CM}$$

$$\boxed{\frac{V_{gs}}{V_{CM}} = \frac{1}{1 + 2g_m R_o}}$$

$$\therefore A_{CM} = \left(\frac{V_o}{V_{gs}}\right)\left(\frac{V_{gs}}{V_{CM}}\right) \rightarrow \text{small} \ll 1$$

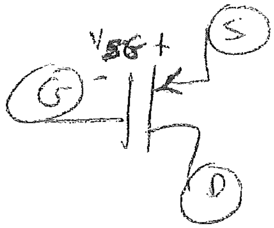
10/17/2016
Madden

$\therefore$ CMRR $= 20\log\left(\frac{A_d}{A_{cm}}\right)$

CMRR can be made large
by increasing R_o

Actively loaded Diff. Amp.

PMOS FETs $\rightarrow$ $I_D = \underbrace{\frac{1}{2}\mu_p C_{ox}\left(\frac{W}{L}\right)}_{k_p}\left(V_{SG} - |V_T|\right)^2$



Saturation condition: $V_{DG} < |V_T|$

$V_{SD} \geq V_{SG} - |V_T|$

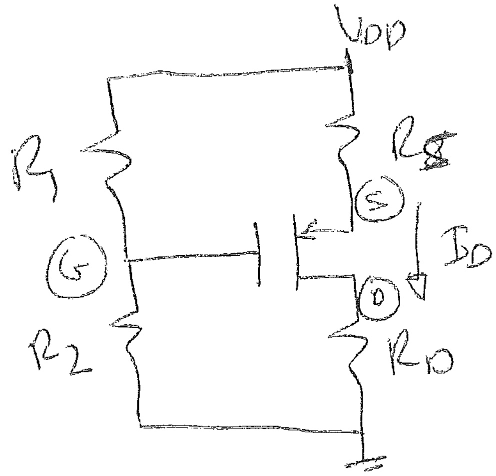
$V_S - V_D \geq V_S - V_G - |V_T|$

$-V_D + V_G \geq |V_T|$

$V_{GD} \geq -|V_T|$

$\boxed{V_{DG} < |V_T|}$

Typical single PMOS amp.



$V_G = \frac{R_2}{R_1 + R_2} V_{DD}$

$V_G + V_{SG} + R_S I_D = V_{DD}$

$V_G + V_{SG} + R_S \frac{k_p}{2}\left(V_{SG} - |V_{Tp}|\right)^2 = V_{DD}$

$\rightarrow$ Solve for V_{SG}.

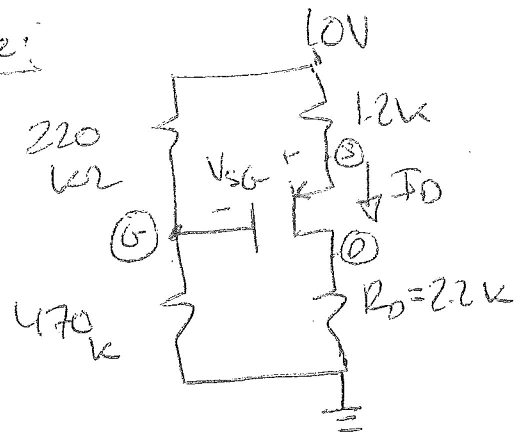
$\rightarrow$ Find I_D

$\rightarrow$ Find V_D

check $V_{GD} = V_G - V_D < V_T$

Example:

$K_p = 1.2\ mA/V^2 \quad V_T = -0.85V$



$$V_G = \left(\frac{470}{470+220}\right)10 = 6.812V$$

KVL equation: $10 - 1.2k\,\underbrace{I_D}_{} - V_{SG} = V_G$ $\quad I_D$

$$10 - 1.2\left[\frac{1}{2}\,1.2\frac{mA}{V^2}(V_{SG}-0.85)^2\right] - V_{SG} = 6.812$$

$$10 - 0.72\,V_{SG}^2 + 1.224\,V_{SG} - 0.5202 - V_{SG} = 6.81$$

$$\boxed{V_{SG} = 2.087V}$$

$$\therefore\quad I_D = 0.6\,(2.087-0.87)^2 = 0.9206\ mA.$$

$$\boxed{V_D = R_D \cdot I_D = (2.2k)(0.9206mA) = 2.025V.}$$

But $V_{GD} < V_T$? $\quad V_G - V_D = 6.812 - 2.025 = 4.8$?

$\therefore$ Make $R_D = 8K$.

then $V_D = 8k(0.9206mA) = 7.365V$

and $V_{GD} = 6.812 - 7.365 = -0.553 < 0.85$

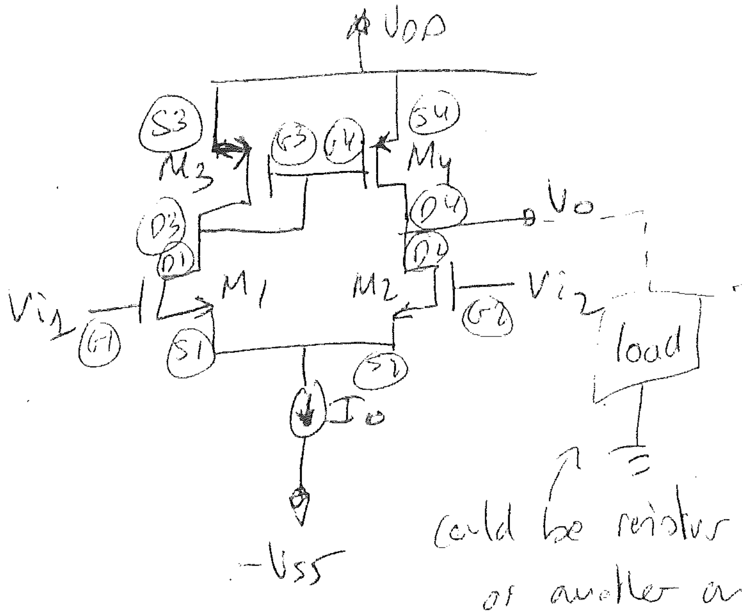
And saturation!

→ CMOS Diff Amp stage

→ w/ load resistance → small gain due to ~~large~~ finite R-value.

→ Increase gain by increasing R_O.
Use mosfet as load to increase gain as effective R_O is large.

2-possibilities
NMOS vs. PMOS
① Drive transistors: receives input signal
② Load transistors: output taken at the drain of this.



Drive transistors: M_1, M_2 (NMOS)
Load transistors: M_3, M_4 (PMOS)

Current follows the arrows of MOSFETs

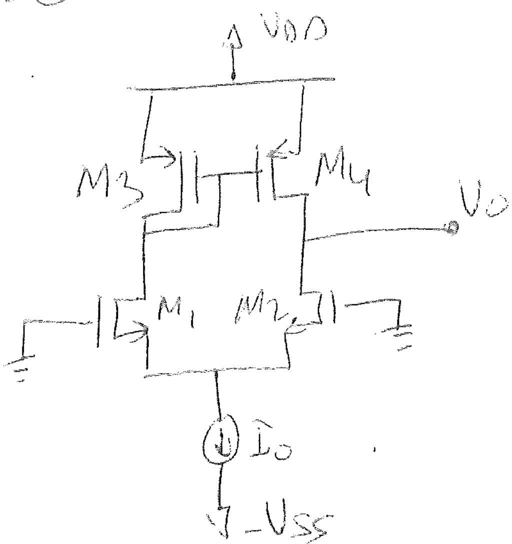
M_1, M_2 are identical → same k and same V_T
M_3, M_4 are identical → " " " " "
→ Often all 4 identical which requires width of PMOS to be ~4x larger than NMOS.

10/19/2016

Madhu

Q-point (DC analysis)

$v_{i1} = v_{i2} = 0V$



Note: $V_{GS1} = V_{GS2}$

$M_1 = M_2$

$\therefore I_{D1} = I_{D2} = \frac{I_O}{2}$

I_O is known.

Find V_{GS1} and V_{DS2} from $\frac{I_O}{2}$

M_3 in series w/ M_1

$\therefore I_{D3} = I_{D1} \rightarrow$ Find V_{DS3}

M_2 in series w/ M_4

$\therefore I_{D2} = I_{D4} \rightarrow$ Find V_{DS4}.

when circuit is perfectly balanced. $\leftarrow$ $\therefore$ No current to the load at Q-point

$\rightarrow$ Find g_{m1}, g_{m2} g_{m3} g_{m4} and r_{o1} r_{o2} r_{o3} r_{o4}. $\Big\}$ From Q-point analysis.

Note: $g_{m1} = g_{m2}$ and $g_{m3} = g_{m4}$

$r_{o1} = r_{o2}$ $\quad$ $r_{o3} = r_{o4}$

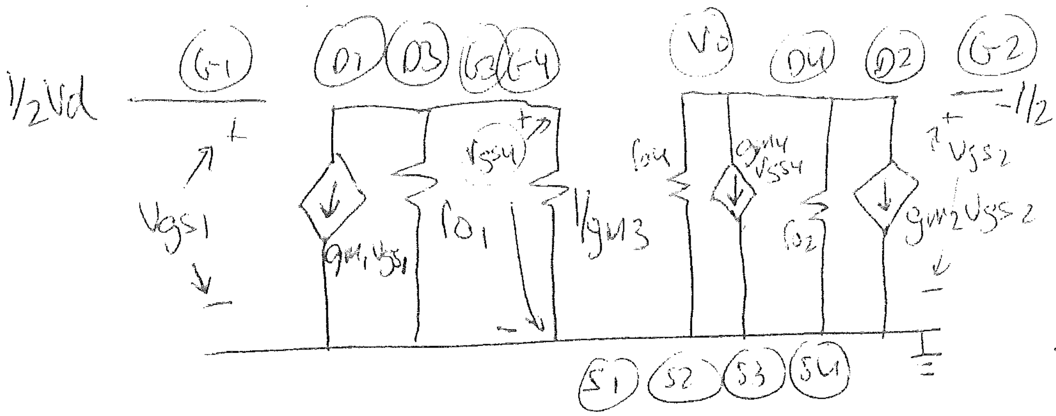
Small-signal analysis – Diff mode

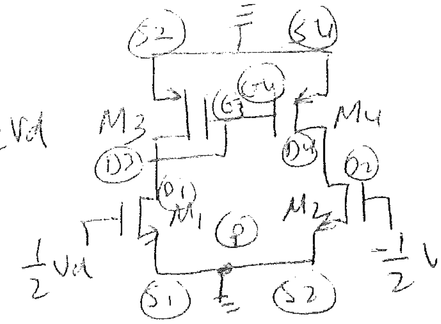
→ Cannot analyze only one-half of circuit.

→ $v_{i1} = \frac{1}{2} v_d \quad v_{i2} = -\frac{1}{2} v_d$

→ Small signal eq. circuit.

- Node (P) is ac. ground
- Ground power supplies
- Start w/ ground line





- All source terminals are ground.
- "Diode connected" → $1/g_m = R$

$V_{gs1} = \frac{1}{2} V_d$

$V_{gs2} = -\frac{1}{2} V_d$

$r_o \to 100$'s $k\Omega$

$g_m \to m$ S

$\therefore \frac{1}{g_{m3}} << r_{o1} \quad \frac{1}{g_m}$'s

→ ignore r_{o1} in parallel combination

→ Find $V_{gs4} = -g_{m1} V_{gs1} \left(r_{o1} \parallel \frac{1}{g_{m3}} \right)$

$V_{gs4} = -g_{m1} V_{gs1} \left(\frac{1}{g_{m3}} \right)$

$V_{gs1} = \frac{1}{2} V_d \longrightarrow$

$V_{gs4} = -\frac{1}{2} \frac{g_{m1}}{g_{m3}} \cdot V_d$

cont'd

cont's

10/19/2016
Madhu (2)

V_o — $-(g_{m4} V_{gs4} + g_{m2} V_{gs2})(r_{ds2} \| r_{ds4}) = V_o$

$$V_o = -\left[g_{m4}\left(-\frac{1}{2}\frac{g_{m1}}{g_{m3}} v_d\right) + g_{m2}\left(-\frac{1}{2} v_d\right)\right](r_{o2}\|r_{o4})$$

$V_{gs2} = -\frac{1}{2} v_d$

$V_{gs4} = -\frac{1}{2} v_d \frac{g_{m1}}{g_{m3}}$

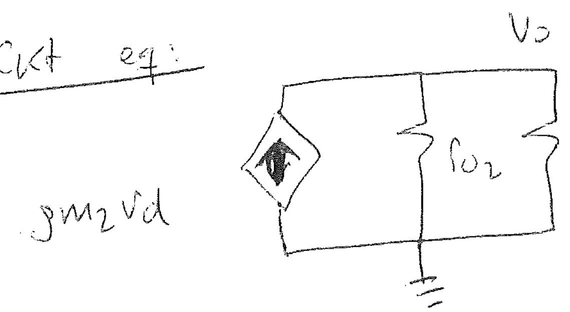
(from before)

$g_{m4} = g_{m3}$
and
$g_{m1} = g_{m2}$

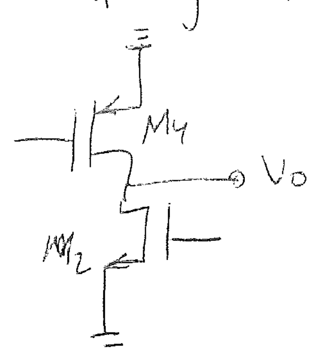
$$V_o = \left(\frac{1}{2} g_{m1} + \frac{1}{2} g_{m2}\right) v_d \, (r_{o2}\|r_{o4})$$

$$V_o = g_{m2} v_d (r_{o2}\|r_{o4})$$ → r_{o2} + r_{o4} are larger than Resistor and smaller. Large gains can be obtain.

→ Ckt eq:



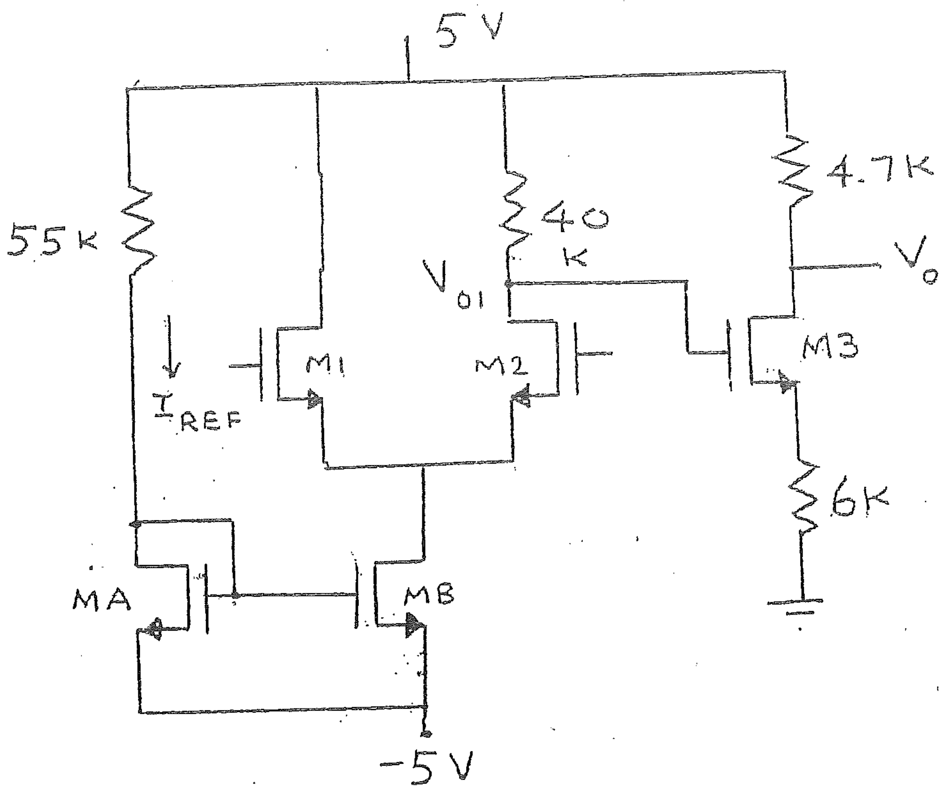
only right half of circuit.



→ only the two transistors connected to Vo. Right hand side

→ Common-mode more complex to derive formula

END → What happens when a load is added

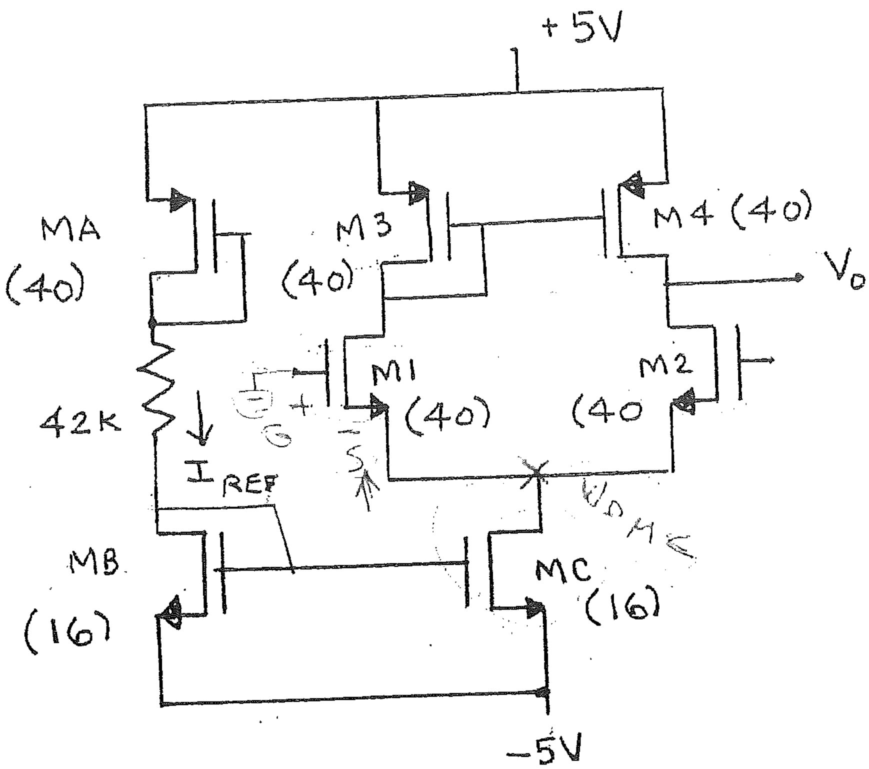


$k_n = 0.2$ mA/V^2

$V_T = 1.2V$

$\lambda = 0.01\ V^{-1}$

DIFFAMP (RESISTIVE LOAD)



$\mu_n C_{ox} = 0.05$ mA/V^2

$\mu_p C_{ox} = 0.02$ mA/V^2

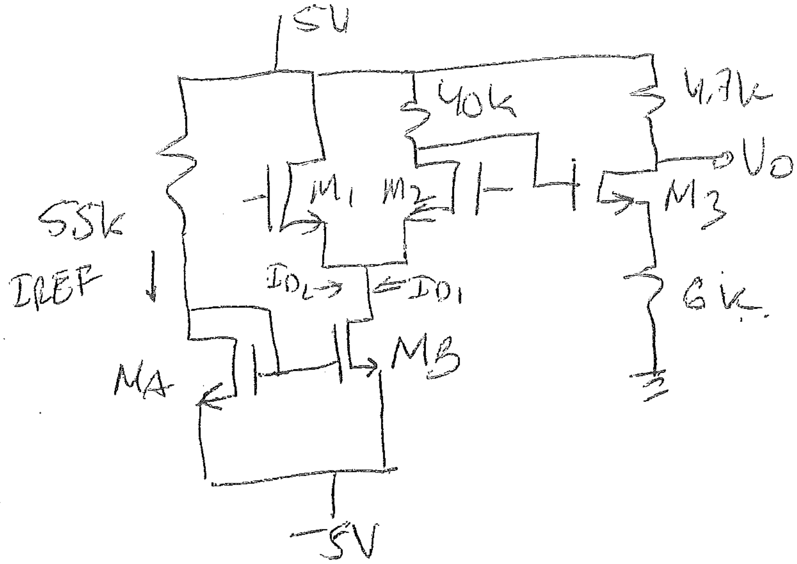
$|V_T| = 1.1V$

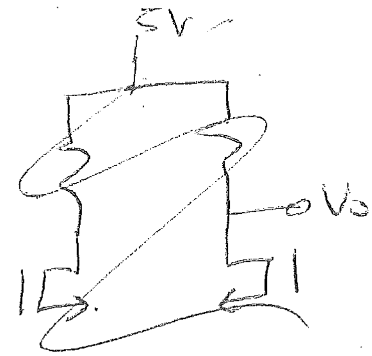
$\lambda = 0.01\ V^{-1}$

NOW 10/21/2016
LECTURE.

→ DIFF. AMP EXAMPLES.

① DC analysis





$k = 0.2\ mA/V^2$
$V_T = 1.2V$
$\lambda = 0.01\ V^{-1}$

$$5 - 55k \cdot I_{REF} - V_{GSA} - (-5) = 0$$

$$5 - 55k\ \frac{1}{2}(0.2mA)(V_{GSA} - \overset{1.2}{V_T})^2 - V_{GSA} - (-5) = 0$$

$$5 - 5.5V_{GSA}^2 + 13.2V_{GSA} - 7.92 - V_{GSA} + 5 = 0$$

$$V_{GSA} = 2.377V$$

And $I_{REF} = 0.1(2.377 - 1.2)^2 = 0.1385mA.$

$\therefore\ I_{D1} = I_{D2} = 0.06926mA$ (irregardless of load resistor)

$V_{GS1}, V_{GS2} \Rightarrow\ \underset{mA}{0.06926} = \frac{1}{2}(0.2mA)\underbrace{(V_{GS1} - V_T)^2}_{V_{OV}^2}$

$$V_{OV} = \sqrt{\frac{2 \times 0.06926mA}{0.2mA}}$$

and $V_{GS1} = V_{GS2} = 2.032V$

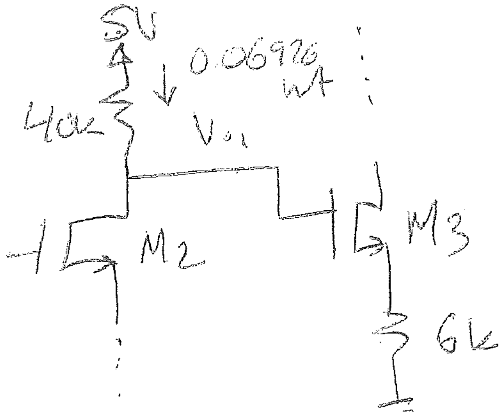
cont'd →

↳ Cont's

6/21/2010

Madhu

→ Find V_{GS3} at M_3



$V_{o1} = 2.229V$

$2.229V - V_{GS3} - 6 \cdot I_{D3} = 0$

$2.229 - V_{GS3} - 6\left(\frac{1}{2} 0.2\,\text{mA/V} (V_{GS3} - V_T)^2\right) = 0$

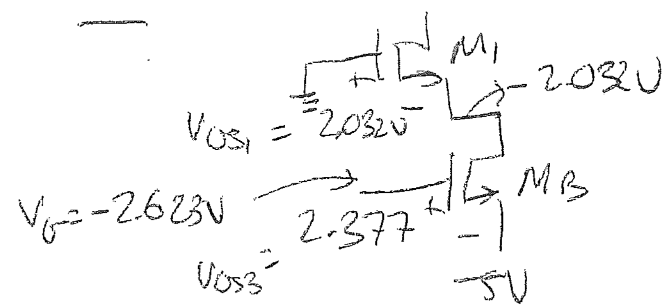
$2.229 - V_{GS3} - 0.6 V_{GS3}^2 + 1.44 V_{GS3} - 0.864 = 0$

Solving polynomial → $V_{GS3} = 1.919$ Volts.

and $I_{D3} = 0.0517$ mA

→ Check for saturation:

M_B: In DC M_1 + M_B are grounded.



V_{GD} of M_B

$\therefore = -2.623 + 2.032$

$= -0.591 < V_T$ OK

or V_{DS} of M_B

$V_{DS} = 5 - 2.032 = 2.9 > 2.377 - 1.2$

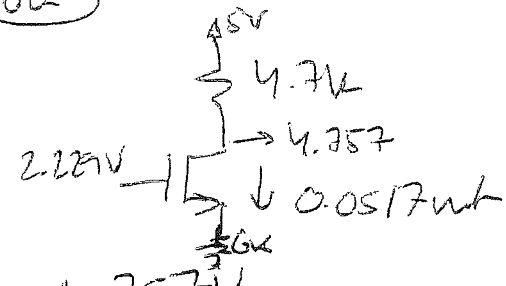
$V_{DS} > V_{GS} - V_T$ OK

M_2: $V_{D2} = 2.229V$

$V_{G2} = 0$

$V_{GD2} = -2.229 < V_T$ OK

~~$V_{GS3} = 1.919V$~~



M_3: $V_{G3} = 2.229V$

$V_{D3} = 5 - 4.7(0.0517) = 4.757V$

$V_{GD3} = -2.528V < V_T$ ok

Small-signal

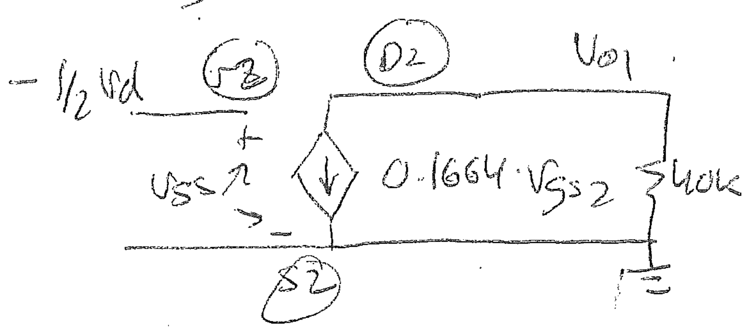
Need g_{m2} and g_{m3}

$g_{m2} = 0.2\,\text{mA/V}\,(2.032 - 1.2) = 0.1664\,\text{mS}$

$g_{m3} = 0.2\,\text{mA/V}\,(1.919 - 1.2) = 0.1438\,\text{mS}$

Diff. mode small-signal analysis:

M2 stage and M3 stage.

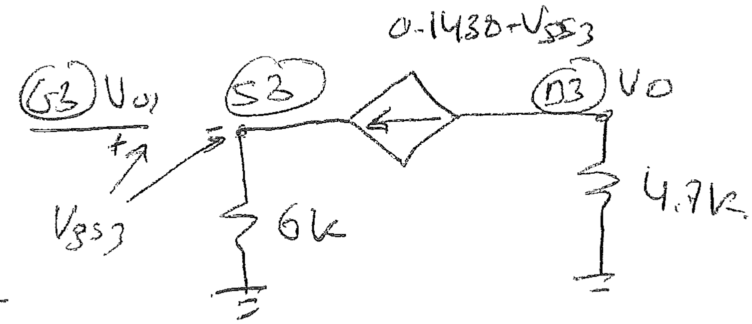


$v_{o1} = -v_{gs2} \cdot g_{m2} \cdot R_D$

$\frac{v_{o1}}{v_{gs2}} = -40k \cdot 0.1664\,\text{mS}$

$\frac{v_{o1}}{v_{gs2}} = -6.656$

M3 stage



C-S stage w/o bypass across 6k.

$\frac{v_o}{v_{gs3}} = -0.1438 \times 4.7 = -0.6759$

$\frac{v_o}{v_{gs3}} = -g_{m3} \cdot 4.7k$

$\frac{v_{gs3}}{v_{g3}} = \frac{1}{1 + g_{m3} \cdot 6k}$

$\frac{v_{gs3}}{v_{g3}} = \frac{1}{1 + 0.1438 \times 6} = 0.53$

$\frac{v_{g3}}{v_{o1}} = 1$ ∴ M3 stage gain:

$(-0.6759)(0.5368)(1) = -0.3628$

cont'd ?

Cont'd Knowing 10/21/2010 Madw ②

$\rightarrow \frac{v_{ss2}}{v_d} = -0.5$ for M_2 stage. and $\frac{v_{o1}}{v_{ss2}} = -6.656$

then

$$\rightarrow \boxed{\frac{v_o}{v_d} = \underbrace{(-0.3628)}_{M3}\underbrace{(-6.656)(-0.5)}_{M2} = -1.208}$$

small gain due to small gm values.

→ load resistances are low

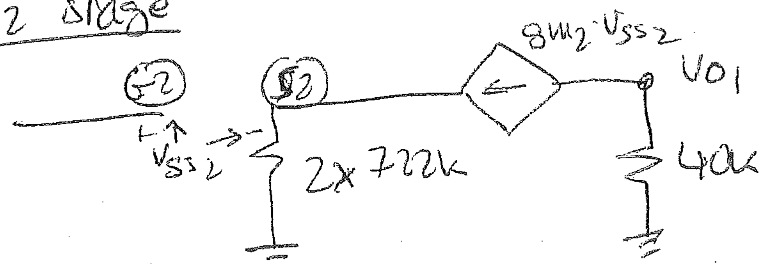
→ w/ MOS loads → gains larger

Common-mode small-signal gain:

Need R_o of current source (M_B) which is equal to $r_{o_{MB}} = \frac{1}{\lambda I_O} = \frac{1}{(0.01)(0.1385mA)}$

$r_o = R_o = 722k\Omega$.

M_2 stage



$\frac{v_{o1}}{v_{ss2}} = -g_{m2} \cdot 40k$

$= -0.1664m (40k)$

$\frac{v_{o1}}{v_{ss2}} = -6.656$

$\frac{v_{ss2}}{v_{s2}} = \frac{1}{1 + g_m(2\times 722k)}$

$\frac{v_{ss2}}{v_{s2}} = \frac{1}{1 + (0.1664m)(2\times 722k)}$

$\frac{v_{ss2}}{v_{s2}} = 4.144 \times 10^{-3}$

$\frac{v_{s2}}{v_{CM}} = 1$

∴ Common-mode gain of M_2 stage.

$$A_v = \frac{v_{o1}}{v_{ss2}} \times \frac{v_{ss2}}{v_{s2}} \times \frac{v_{s2}}{v_{CM}} = -0.02759$$

Common-mode gain of M_3 stage
→ same as before because it is not a diff stage.

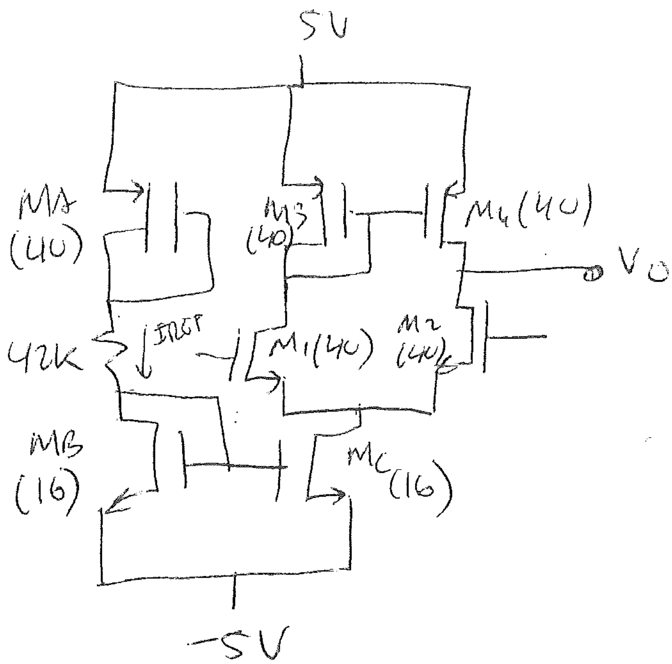
$$A_{M_3} \doteq -0.3628$$

$$\therefore \quad A_{CM} = (-0.02759)(-0.3628) \cong 0.01$$

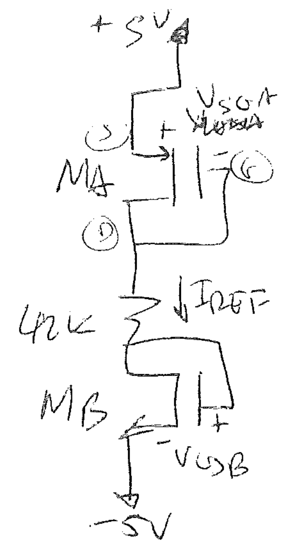
end lecture

---

start lecture. CMOS Diff. amp w/ active load example.
↳ using MOSFETs as load.



→ current source MA, 42k, MB + MC



MA: PMOS 0.02mA/V²

$K_p = \mu_p C_{ox} \cdot \frac{W}{L}$

$K_p = (0.02)(40)$

$K_p = 0.8\,mA/V^2$

MB: NMOS

$K_n = \mu_n C_{ox} \cdot \frac{W}{L}$

$K_n = (0.05)(16)$

$K_n = 0.8\,mA/V^2$

$$5 - V_{SGA} - 42 \cdot I_{REF} - V_{GSB} = -5$$

$$\left.\begin{array}{l} M_A \rightarrow I_{REF} = \frac{1}{2}(0.8)(V_{SGA} - 1.1)^2 \\ M_B \rightarrow I_{REF} = \frac{1}{2}(0.8)(V_{GSB} - 1.1)^2 \end{array}\right\} \therefore V_{SGA} = V_{GSB}$$

then → $5 - V_{GSB} - 42\left(\frac{1}{2}(0.8)(V_{GSB} - 1.1)^2\right) - V_{GSB} = -5$

$$10 - 2V_{GSB} - 16.8V_{GSB}^2 + 36.96V_{GSB} - 20.33 = 0$$

$$\boxed{V_{GSB} = 1.724\text{ Volts} = V_{SGA}}$$

And $I_{REF} = \frac{1}{2}(0.8)(1.724 - 1.1)^2 = \cancel{.1558\,mA}$ $0.1558\,mA$

cont'd

e cont'd 10/24/16

Madhu.

→ Current splits ½ thru diff. pair:

$I_{D_1} = I_{D_2} = \frac{I_{REF}}{2}$

$k_n' = \mu_n C_{ox}$ W/L $1.1V$

$I_{D_1} = I_{D_2} = 0.07783\,\mu A$

→ and $0.07783\,\mu A = \frac{1}{2}(0.05\,\mu A/V^2)(40)(\underbrace{V_{GS_1} - V_T}_{V_{OV}})^2$

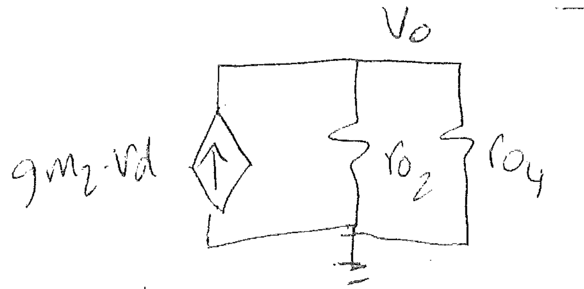
$V_{OV} = V_{GS_1} - 1.1 = 0.2791$

$V_{GS_1} = 1.379V$

→ $g_{m_1} = g_{m_2} = k_n(V_{GS} - V_T) = \cancel{0.2232\ mS}$

$(0.05 \times 40)(0.2791)$ $0.558\ mS$

eq. circuit of diff amp



→ need r_{o_2} and r_{o_4} (right side of diff. amp circuit)

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

1.28M

$r_{o_2} = \frac{1}{(\underbrace{0.07788\,\mu A}_{I_D})(\underbrace{0.01}_{\lambda})V^{-1}} = \cancel{128.}$ k

$V_o = g_{m_2} \cdot v_d \cdot (r_{o_2} \| r_{o_4})$

$A_d = \frac{v_o}{v_d} = g_{m_2}(r_{o_2} \| r_{o_4})$

$\boxed{r_{o_4} = r_{o_2} = \cancel{128.4\,k\Omega}}$ $1.284\,M\Omega$

then $A_d = 0.558\,mS\left(\frac{1284\,k\Omega}{2}\right)$

$\boxed{A_d = 358.2\ V/V}$

common-mode:

$A_{CM} = -\frac{1}{2 g_{m_3} R_o} =$

$g_{m_3} = k_p(V_{GS} - V_T) = 0.3528\,mS$

$R_o = 6418\,k\Omega$

$A_{CM} = -22\,mV/V$ $CMRR = 104.24\,dB$

cont'd in next sheet

CONTINUES FROM COMMOM-MODE ANALYSIS OF PREVIOUS EXAMPLE

10/24/16

(1A)

$\cancel{\frac{v_o}{v_{ss}} = -g_m R_1}$

$$k_p = 40(0.02) \; f(V_{GS_3} - V_T)$$

$$0.07778 \text{ mA} = \frac{1}{2}\, 0.8\, (V_{GS_3} - V_T)^2$$

$$\frac{0.07778}{0.4} = V_{OV}^2$$

$V_{OV} = 0.441 V \rightarrow V_{GS3} = 0.441 + 1.1 = 1.54V$

$\rightarrow g_{m3} = 0.8(0.441) = 352.8 \mu S \quad 0.3528 mS$

$$\rightarrow R_O = \frac{1}{\lambda I_D} = \frac{1}{0.01 \cdot 0.1558 \text{ mA}} = 641.8 k\Omega$$

r_{O_C}

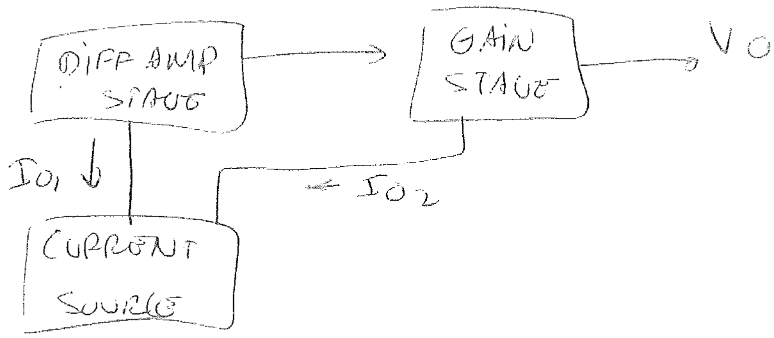
$$A_{CM} = -\frac{1}{457.9} = -2.2 \text{ mV/V}$$

$$CMRR = 20 \log \frac{358.2 \text{ V/V}}{0.0022 \text{ V/V}} = 104.24 \text{ dB}$$

HW#6 - ~~9.1~~ 9.1, 9.5, 9.6 ← (Problems)

Chapter Exercises → 9.5 (page 611), 9.17 (page 648), 9.20 (page 657,

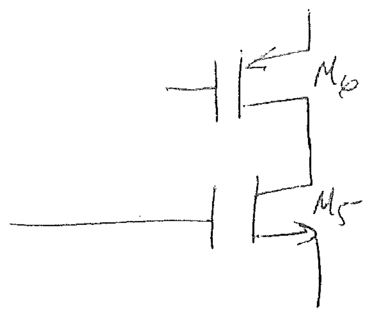
Another example.
→ 2-stage CMOS op-AMP {→ with feedback loop}
(DIFF AMP)



output stage (leave later) w/ low output resistance.

Gain stage → output from diff. amp

load for gain stage



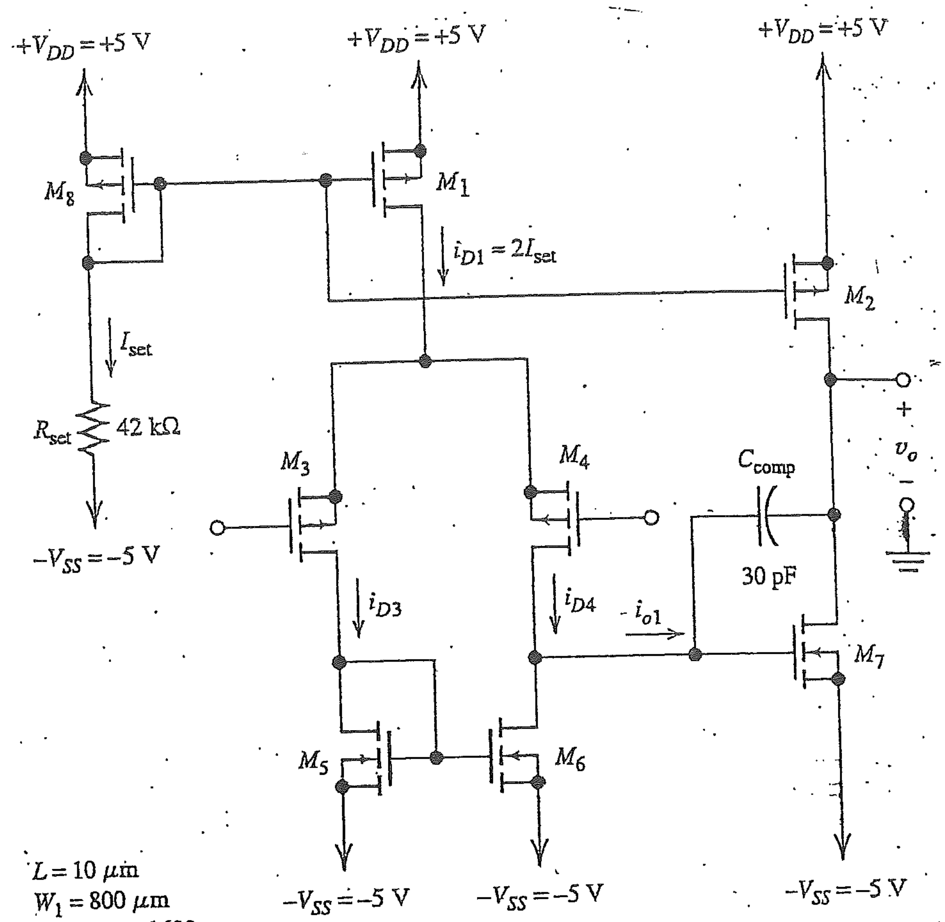
driver of gain stage

vo from diff. stage

→ load on M_5 is r_{o6} of the load. (large gains)

→ gain is $\propto g_{m5}$ and r_{o6}) . . .

→ common source amplifier.



$L = 10\ \mu m$
$W_1 = 800\ \mu m$
$W_2 = W_7 = 1600\ \mu m$
$W_3 = W_4 = W_5 = W_6 = W_8 = 400\ \mu m$

$$\mu_p C_{ox} = 0.025\ mA/V^2$$

$$\mu_n C_{ox} = 0.05\ mA/V^2$$

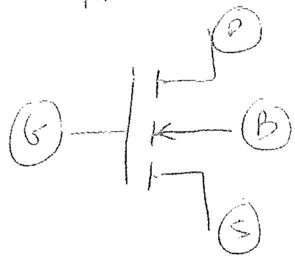
$$|V_T| = 1\ V$$

$$\lambda = 0.01\ V^{-1}$$

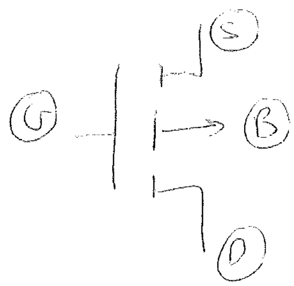
Basic CMOS Op Amp

10/24/2016
(2)
Madhu.

NMOS



PMOS



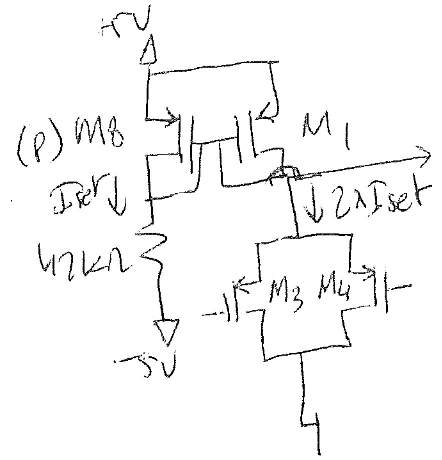
Arrow always goes from P → N.

→ Basic CMOS opamp example.

NMOS: M5 M6 M7

PMOS: M1 M2 M3 M4 M8

Re-draw w/ basic MOS symbols.



→ M8: $K = 0.025(40) = \cancel{0.8}\ 1\ mA/V^2$

$V_T = |1V|$

KVL: $5 - V_{SG8} - I_{set}(42k\Omega) - (-5) =$

$5 - V_{SG8} - \frac{1}{2}\ 1mA/V^2 (V_{SG8} - 1)^2 \cdot 42k\Omega + 5 = 0$

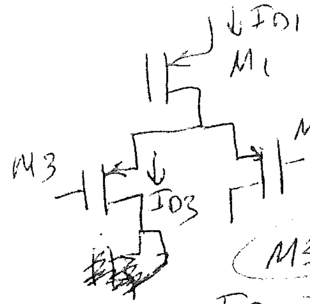
develop step

$5 - V_{SG8} - 21 V_{SG8}^2 + 42 V_{SG8} - 21 + 5 = 0$

$V_{SG8} = 1.631$ Volts.

$\therefore I_{set} = \frac{1}{2}\ 1mA(1.631 - 1)^2$

$= 0.1991\ mA.$



→ M1: Current mirror of M8 but with ~~the~~ twice the width. (same V_{GS})

$I_{D1} = 0.3982\ mA.$

M3:

→ $I_{D3} = 0.1991\ mA$

$I_{D3} = I_{D4} = I_{D5} = I_{D6}$

→ M2 $\frac{W}{L} = 160$

$I_{D_2} = 4 \times I_{D8} = 4 \times I_{sor} = 4 \times 0.1991\,mA = 0.7964\,mA.$

$I_{D2} = I_{D7}$

Need:

fd:

(1) Diff pair:
- M_4 (Driver of diff pair) → g_{m4} → V_{gs4}; r_{o4} → I_{D4}
- M_6 (load of diff. pair) → r_{o6} → I_{D6}

Second stage:
- M7 (driver): → g_{m7} → V_{GS7}; r_{o7} → I_{D7}
- M2 (load): → r_{o2}

→ M_4 PMOS: $I_{D4} = 0.1991\,mA = \frac{1}{2} k'_{P}(V_{SG4} - 1)^2 = \frac{1}{2}(0.025\,mA/V^2) \cdot \frac{400}{10}(V_{SG4} - 1)^2$

$0.1991\,mA = \frac{1}{2}\,1\,mA/V^2\,(V_{OV})^2$

$V_{SG4} = 1.631\,V$

$g_{m4} = 1\,\frac{mA}{V^2}(1.631 - 1) = 0.631\,m$

$r_{o4} = \frac{1}{\lambda I_{D4}} = \frac{1}{0.01V^{-1} \cdot 0.1991\,mA}$

$\boxed{r_{o4} = 502.3\,k\Omega}$

→ M_6 NMOS: $r_{o6} = \frac{1}{\lambda I_{D6}} = \frac{1}{(0.01V^{-1})(0.1991\,mA)} = \boxed{502.3\,k\Omega = r_{o6}}$

→ M_7 NMOS: $K_7 = 0.05\,mA/V^2\left(\frac{1600}{10}\right) = 8\,mA/V^2$

$I_{D7} = 0.7964\,mA = \frac{1}{2}\,8\,mA/V^2\,\underbrace{(V_{GS7} - 1)^2}_{V_{OV}^2}$

$V_{OV} = 0.446\,V$

$\boxed{r_{o7} = \frac{1}{0.01V^{-1}(0.7964)} = 125.6\,k\Omega}$

$V_{GS7} = V_{OV} + 1 = 1.446\,V$ → $g_{m7} = 8\frac{mA}{V}(0.446$

$\boxed{g_{m7} = 3.568\,mS}$

10/26/2016
Madhui

. ↳ contd

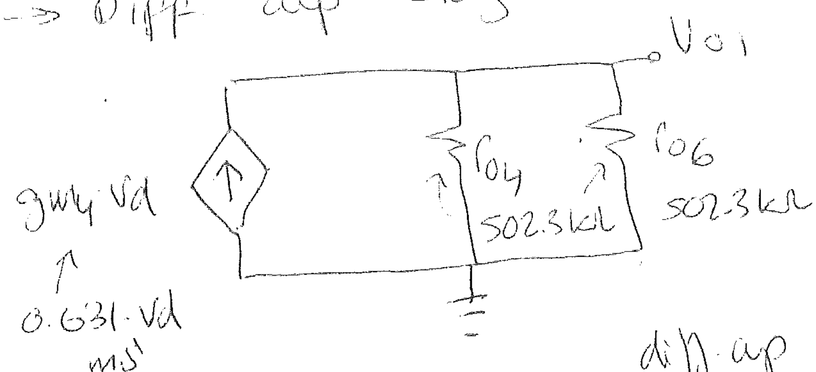
→ (M2) PMOS

$$r_{o2} = \frac{1}{I_{D_2}\lambda} = \frac{1}{(0.01V^{-1})(0.7964mA)}$$

$$\boxed{r_{o2} = 125.6k\Omega}$$

Diff. mode gain: Ad.

→ Diff. amp stage



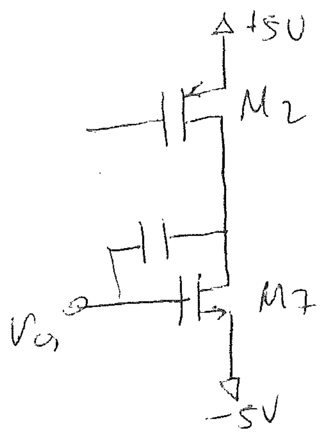
∴ $v_{o1} = g_{m4} \cdot v_d (r_{o4} || r_{o6})$

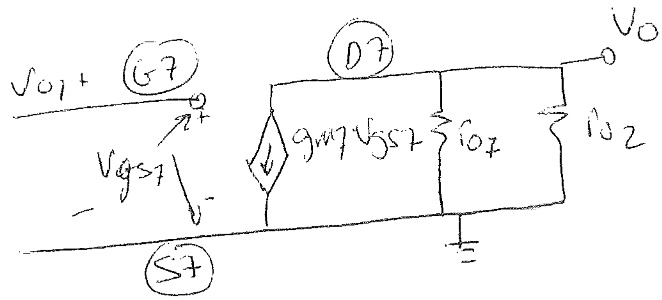
$$\frac{v_{o1}}{v_d} = A_d = (0.631\,mS)\left(\frac{502.3k}{2}\right)$$

diff. amp stage: $\boxed{\frac{v_{o1}}{v_d} = A_d = 158.5\ V/V}$

→ Second stage: M_2 and M_7

→ capacitor acts as open in quasi frequency.





$v_{o1} = v_{gs7}$

$g_{m7} = 3.568\,mS$

$r_{o7} = r_{o2} = 125.6k\Omega$

∴ $v_o = -g_{m7} \cdot v_{gs7} (r_{o7} || r_{o2})$

$$\frac{v_o}{v_{o1}} = -3.568\,mS\left(\frac{125.6k\Omega}{2}\right) = -224.1$$ Second stage

∴, Overall gain $= A_d = (158.5)(-224.1) = -3.55 \times 10^4$

or $A_d = 91dB$