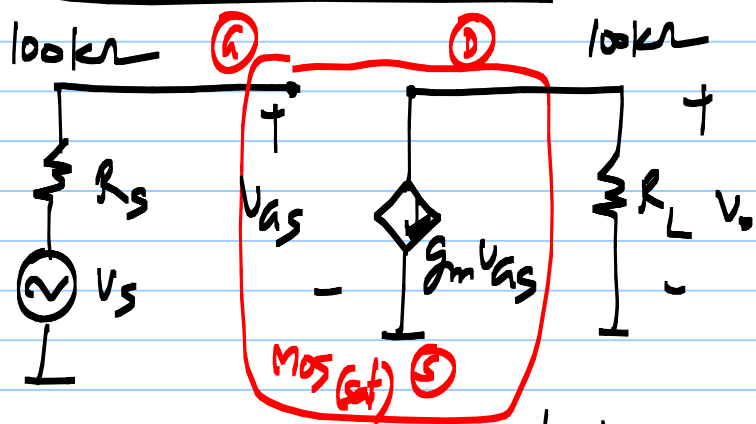
Two-port amplifier



$$\left.\begin{array}{l}\mu_n C_{ox} = 100\,\mu A/V^2 \\ W/L = 1\end{array}\right] \quad K_n = 100\,\mu A/V^2, \quad V_T = 1V$$

$$g_m = \underbrace{\mu_n C_{ox} \frac{W}{L}}_{K_n} (V_{GS} - V_T)$$

$$\Rightarrow \quad V_{GS} - V_T = 2V \Rightarrow$$

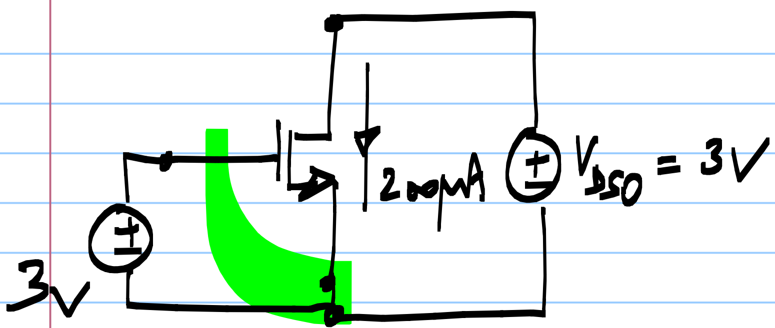
$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (V_{GS} - V_T)^2$$

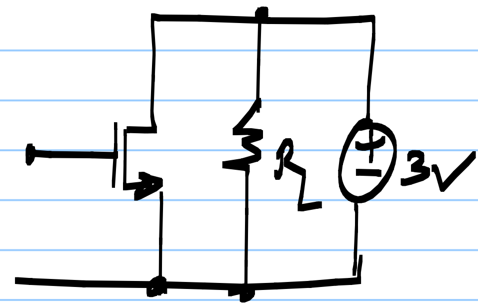
$$=$$

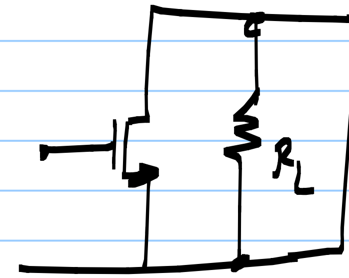
$$v_o = \underbrace{(-g_m R_L)}_{-20 \,=\, -g_m R_L} v_s \qquad |A_v| = 20$$

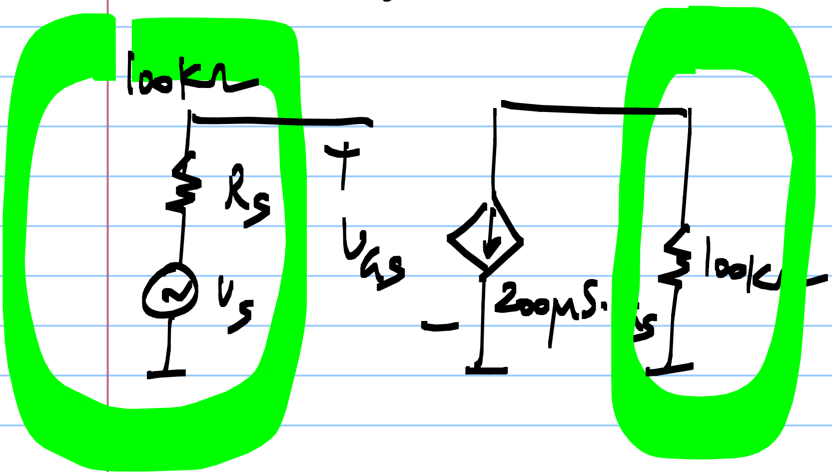
$$g_m = \frac{-20}{-100k\Omega} = 200\mu S$$

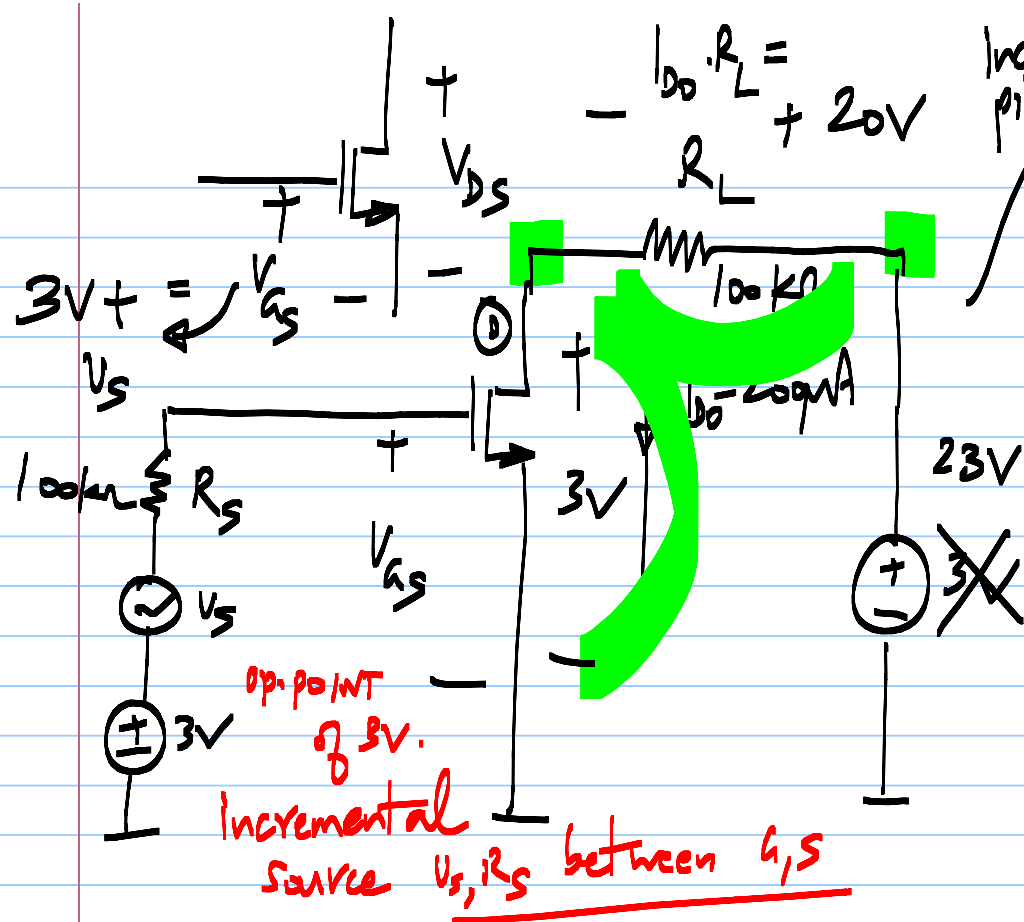
$V_{DSO} \geq V_{GS} - V_T \qquad 2V$



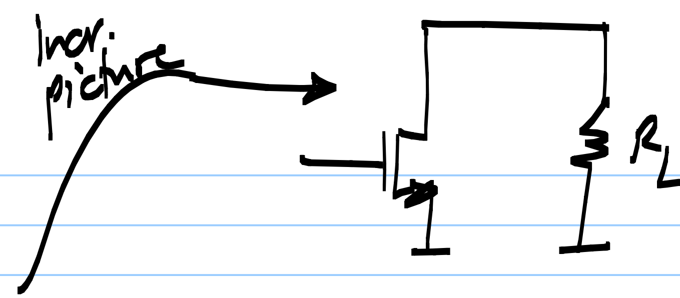








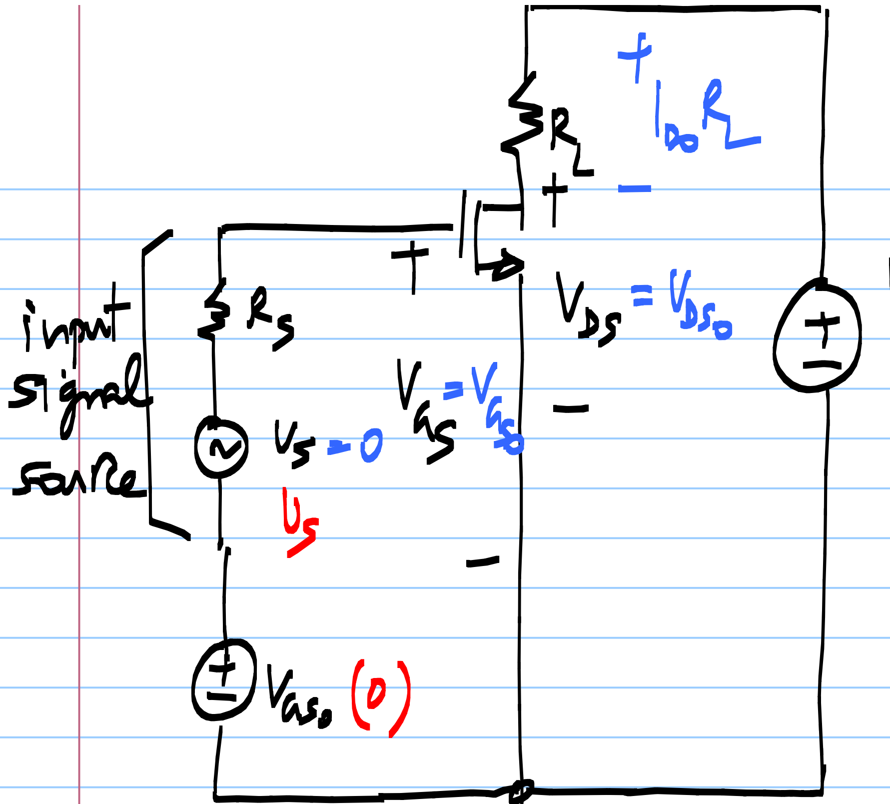
3V + = V_{GS}
V_{DS}
$I_{DO} \cdot R_L$ = + 20V
R_L
100kΩ
I_{DO} = 200µA
D
3V
23V
V_S
100kΩ
R_S
V_{GS}
v_s
3V
op. point of 3V.
incremental source v_s, R_S between G,S



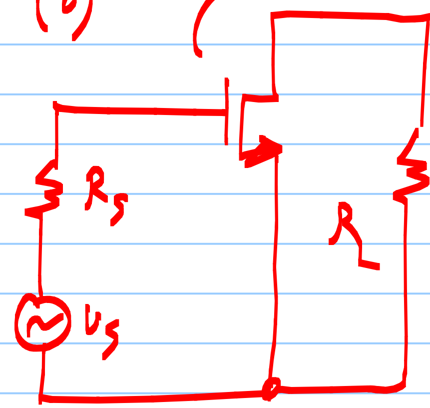
Incr. picture
R_L

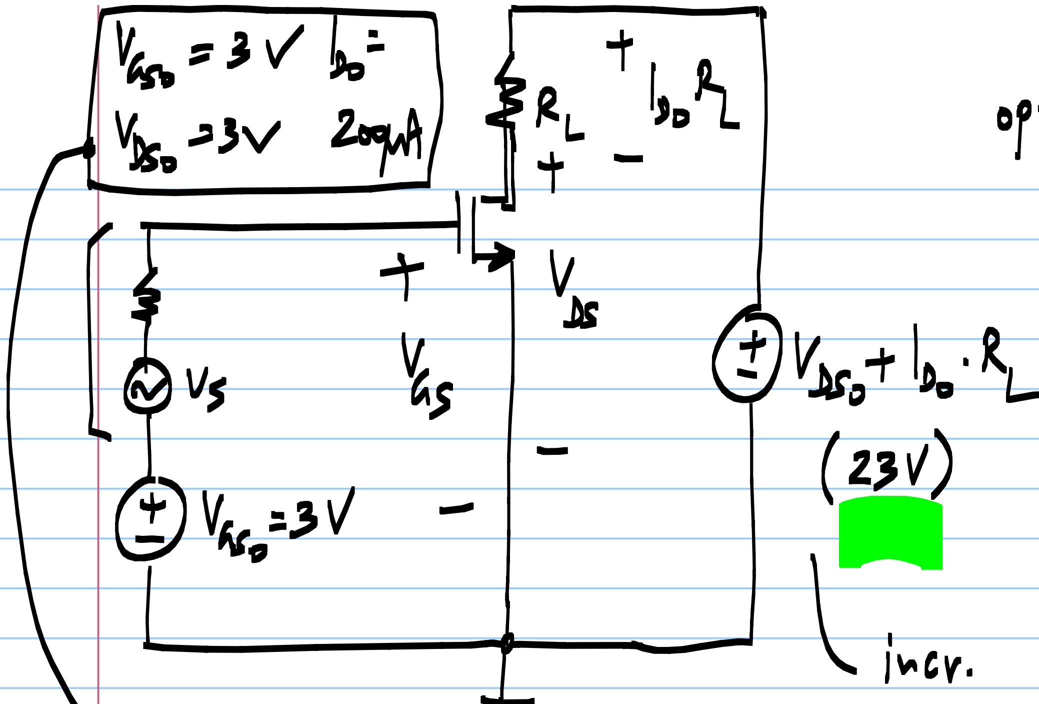
op. point

incr. picture



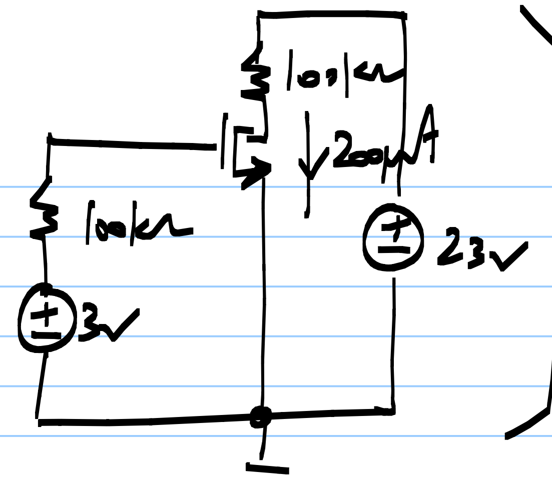
incr. eq.

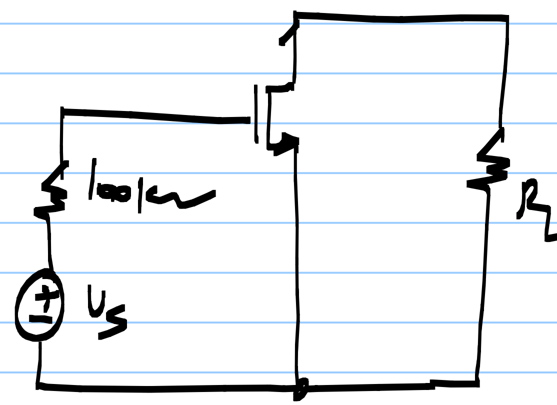


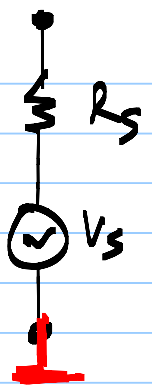


$g_m = 200\mu S$

op. point

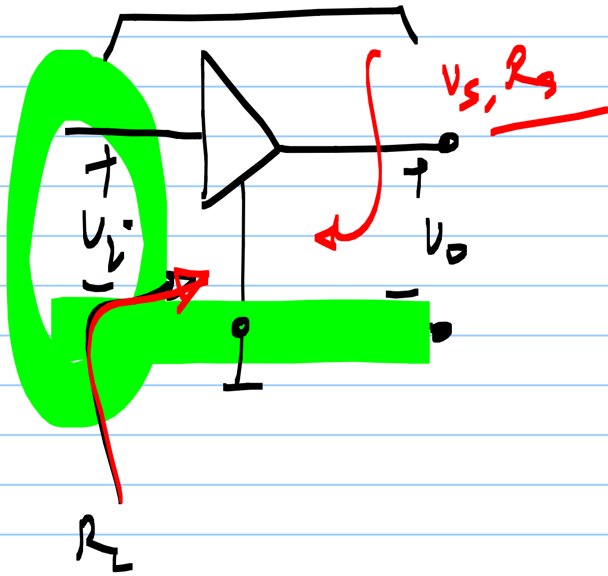






Representation of the input source

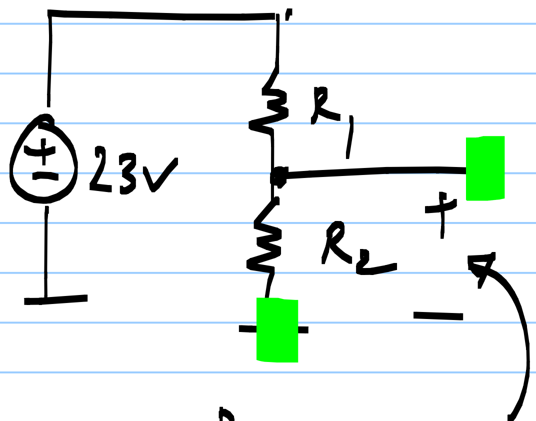
(ground : Common ref. node of the circuit)



Representation of load

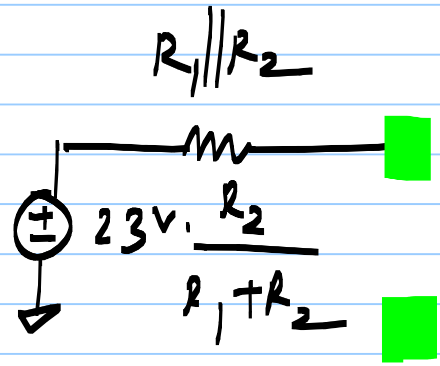
* The source & load are not ground referenced
* Needs multiple dc bias sources

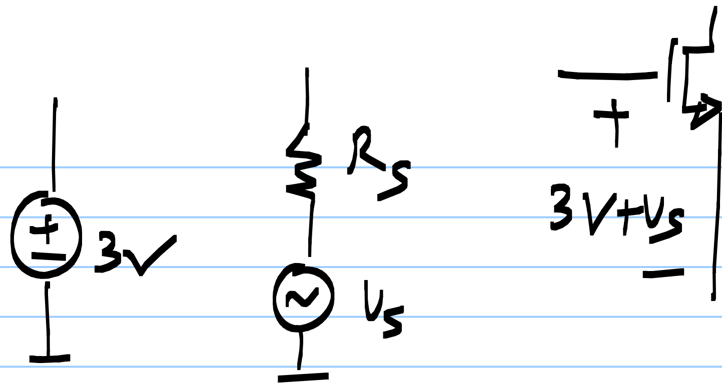
23V, 3V

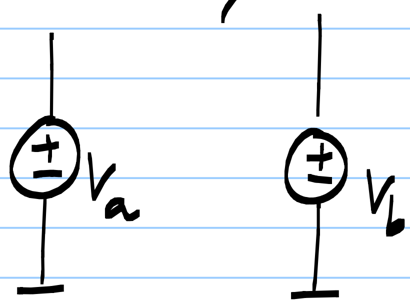


$$23V \cdot \frac{R_2}{R_1+R_2}$$

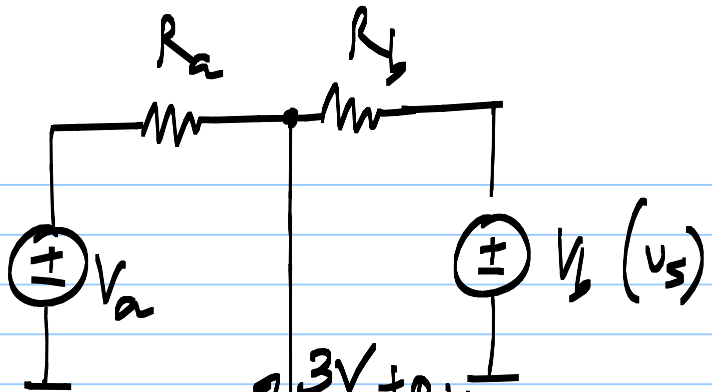
≡







$\alpha V_a + \beta V_b$



$3V + \beta v_s$

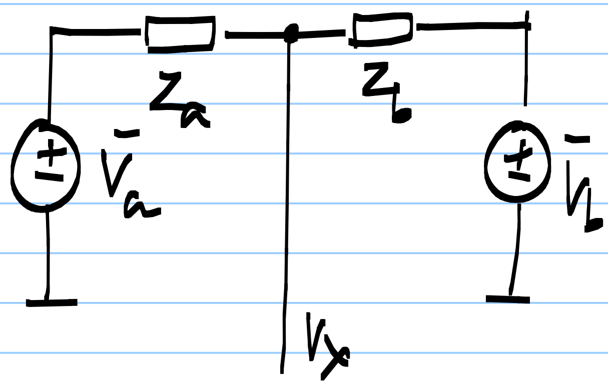
$\alpha V_a + \beta V_b$

linear combination of V_a & V_b

$$V_a \cdot \frac{R_b}{R_a + R_b} + V_b \cdot \frac{R_a}{R_a + R_b}$$

V_a : dc bias

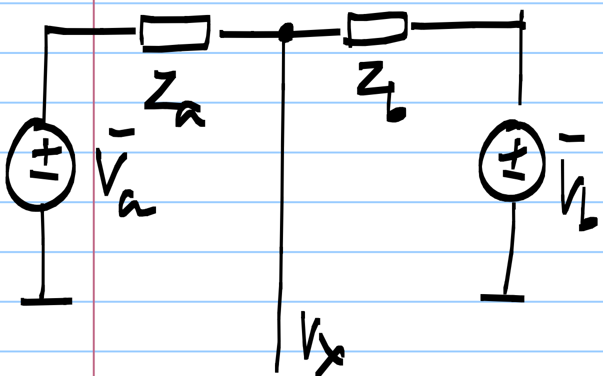
V_b : signal – sinusoid of some frequency $w_0 > 0$



Sinusoidal steady state analysis
(Phasor analysis)

$$\bar{V}_x = \bar{V}_a \cdot \frac{Z_b}{Z_a + Z_b} + \bar{V}_b \cdot \frac{Z_a}{Z_a + Z_b}$$

dc, ω_0



dc

$$V_a(dc) \cdot \underbrace{\frac{Z_b(0)}{Z_a(0) + Z_b(0)}}_{\simeq 1,\ Z_b(0) \gg Z_a(0)} + 0$$

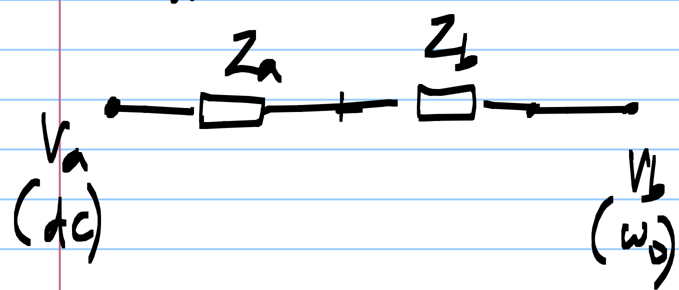
ω_0

$$0 + \bar{V}_b \cdot \underbrace{\frac{Z_a(\omega_0)}{Z_a(\omega_0) + Z_b(\omega_0)}}_{\simeq 1 \quad Z_a(\omega_0) \gg Z_b(\omega_0)}$$

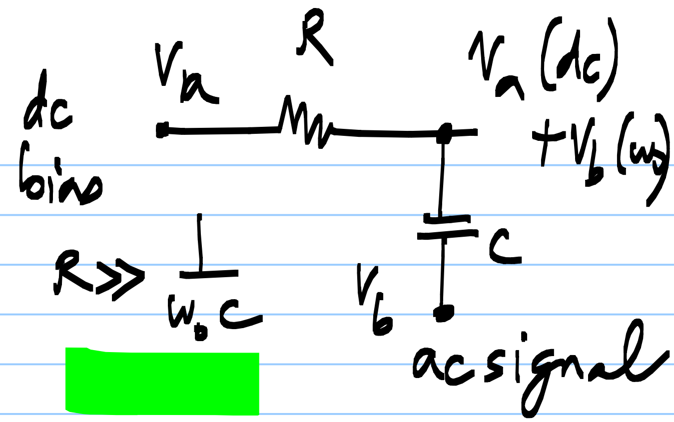
$$\bar{V}_x = \bar{V}_a \cdot \frac{Z_b}{Z_a + Z_b} + \bar{V}_b \cdot \frac{Z_a}{Z_a + Z_b}$$

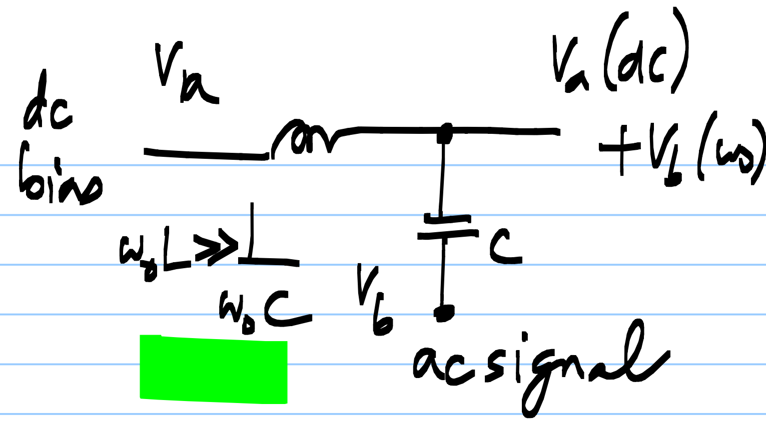
$Z_b(0) \gg Z_a(0)$

$\checkmark$ $Z_a(\omega_0) \gg Z_b(\omega_0)$.

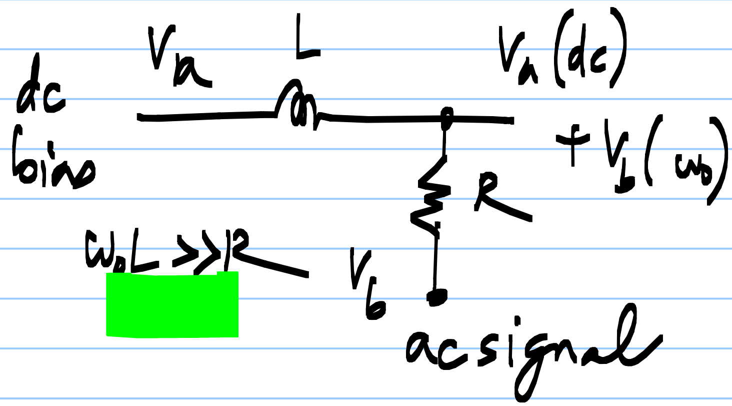


	Z_a	Z_b
1	R	C $\left\{R \gg \frac{1}{\omega_0 C}\right\}$
2	L $\{\omega_0 L \gg R\}$	R
3	L $\left(\omega_0 L \gg \frac{1}{\omega_0 C}\right)$	C

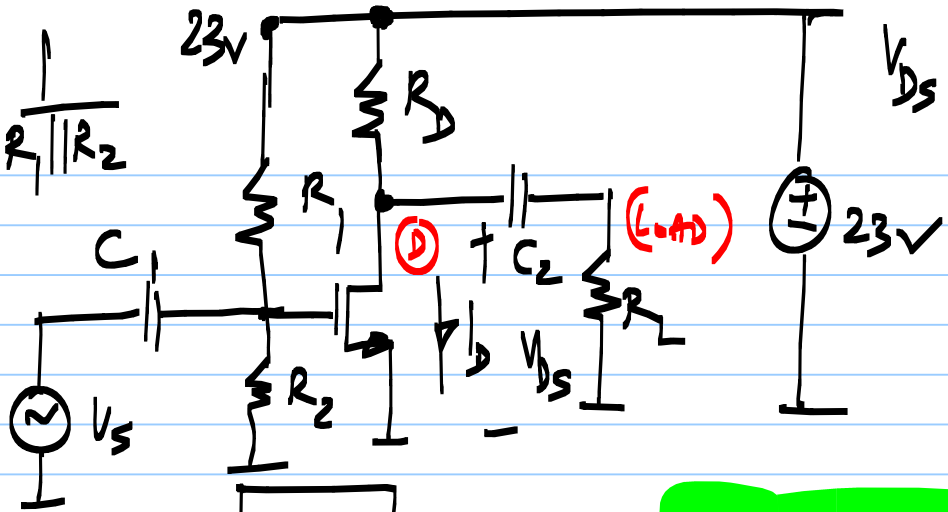




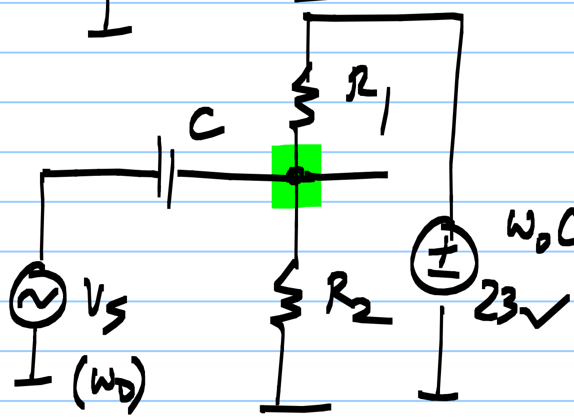
ac coupling networks



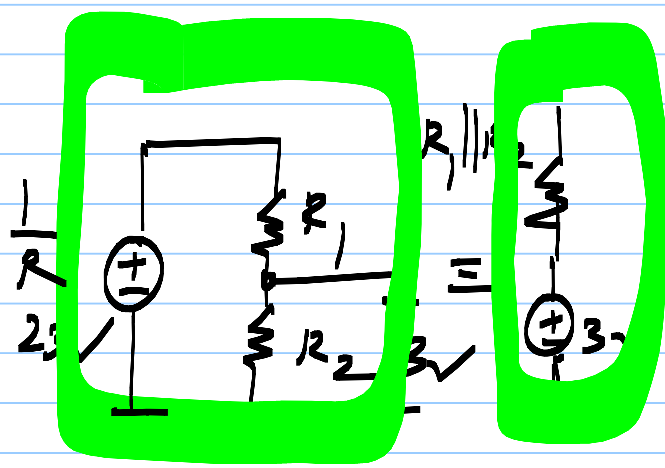
$$\omega_0 C \gg \frac{1}{R_1 || R_2}$$

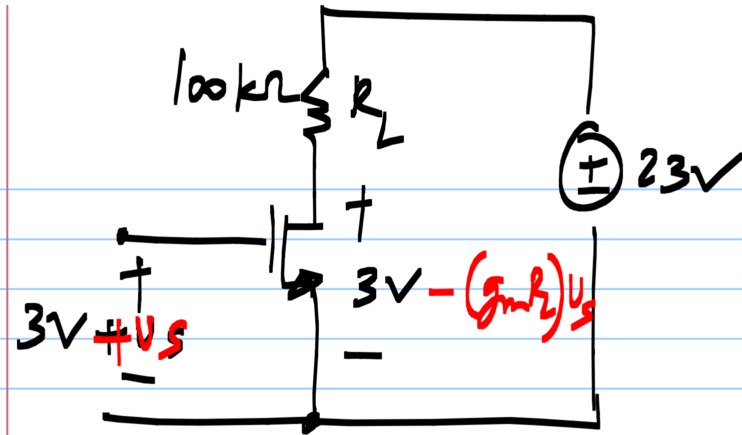


$$V_{DS} > V_{GS} - V_T$$

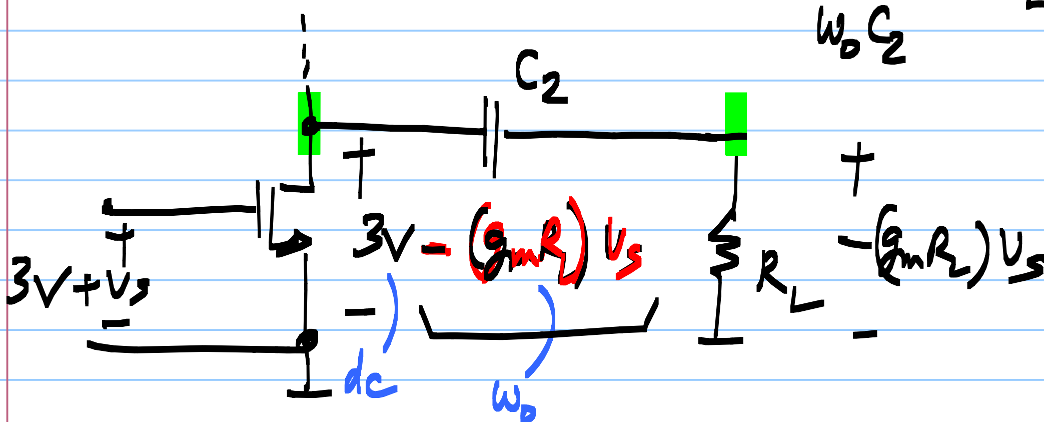


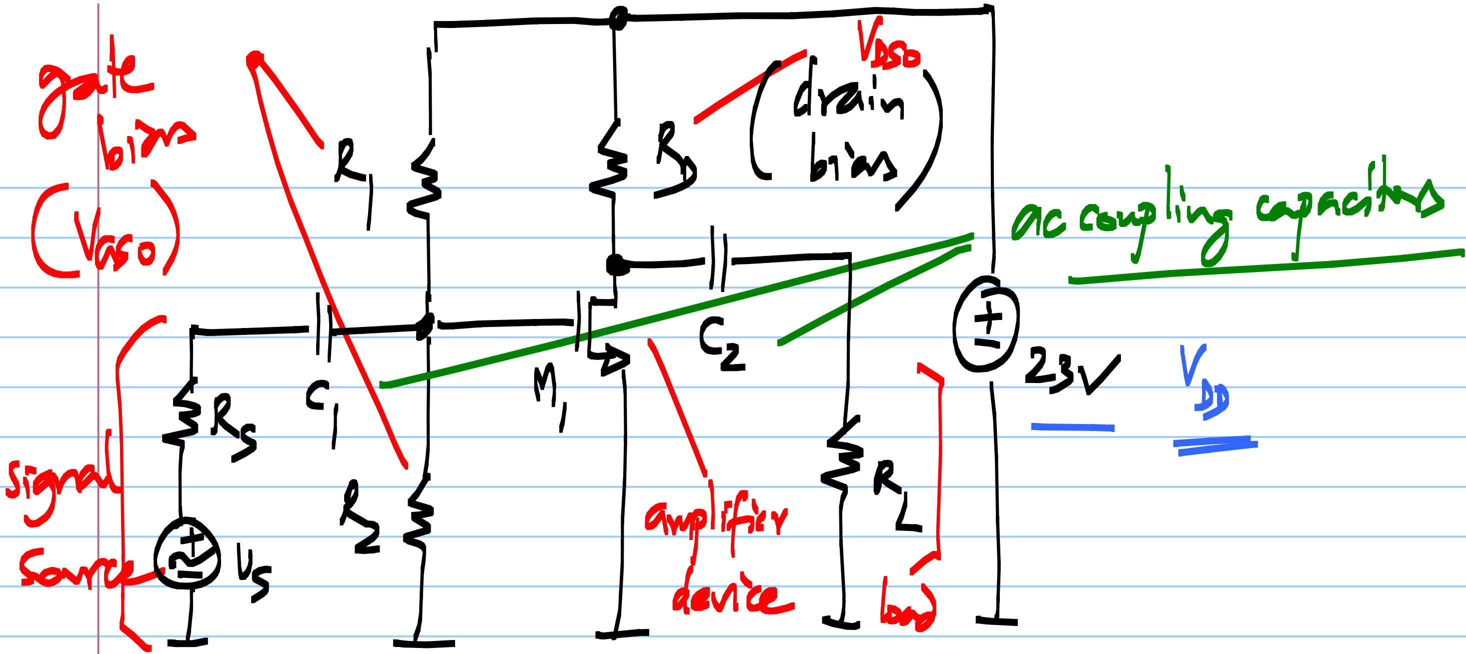
$$\omega_0 C \gg \frac{1}{R}$$



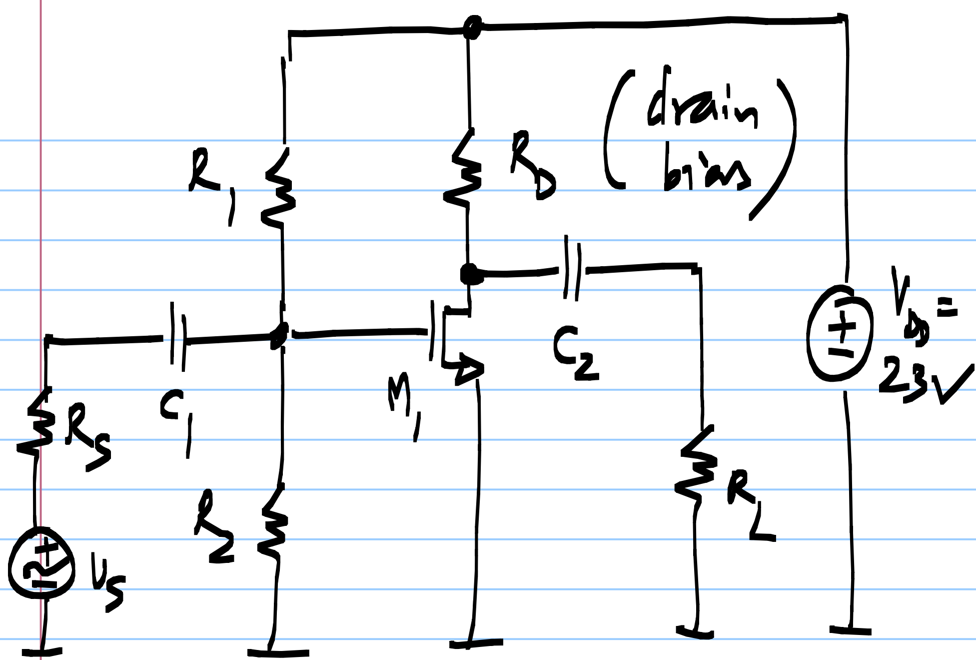


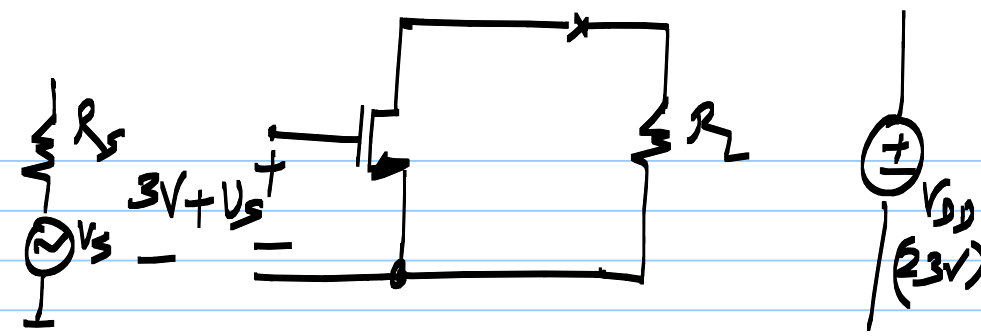
$$\frac{1}{\omega_o C_2} \ll R_L$$





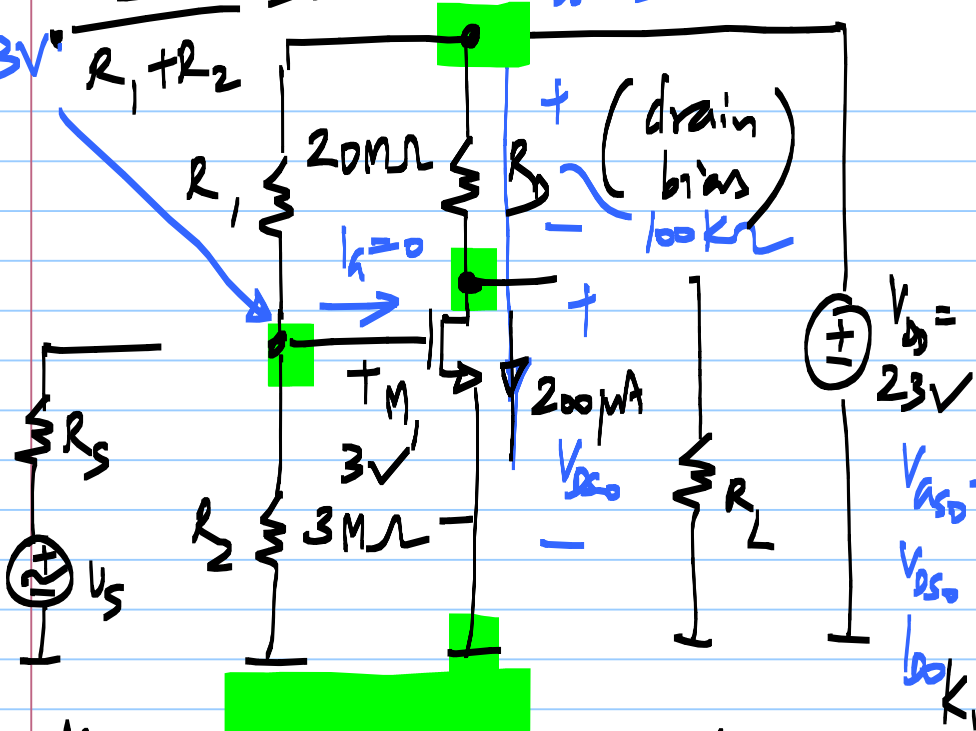
MOS common-source amplifier





MOS common source amplifier

$$23V \cdot \frac{R_2}{R_1 + R_2} = 3V$$



MOS Common source amplifier

operating point (dc)

open circuit capacitors

short circuit inductors

$$\underset{23V}{V_{DS_0}} = V_{DD} - \underset{200\mu A}{I_D}\, \underset{100k\Omega}{R_D} = 3V$$

$V_{GS_0} = 3V$

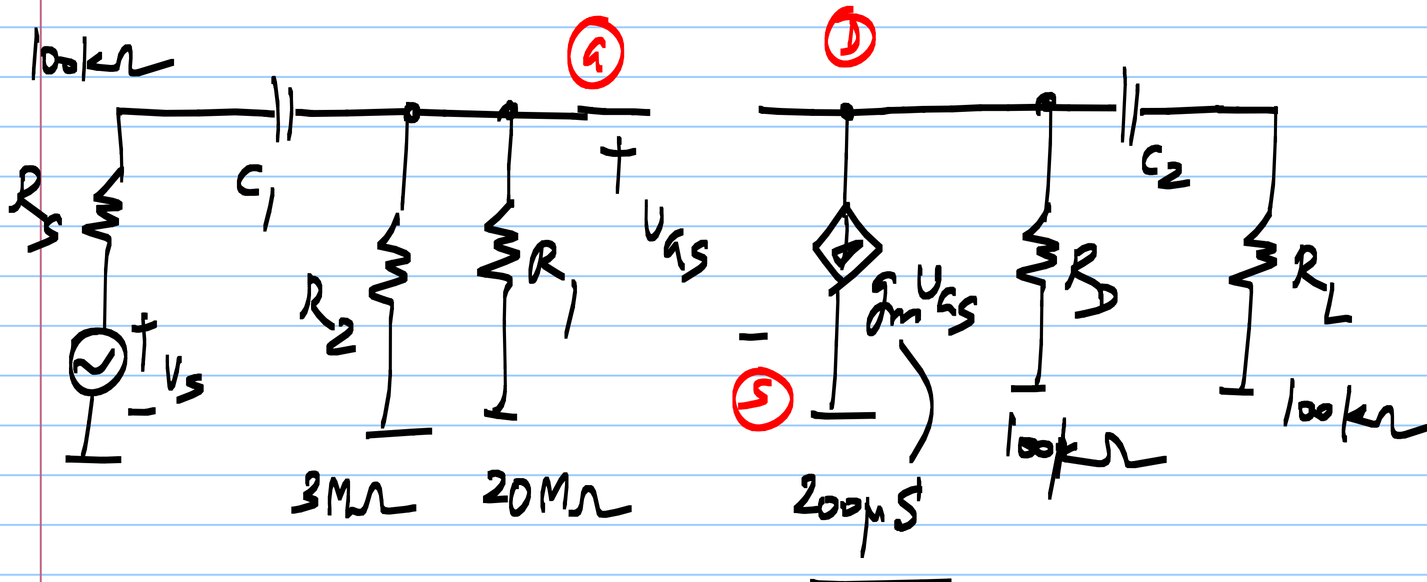
$V_{DS_0} = 3V$

$I_{D0} = 200\mu A$

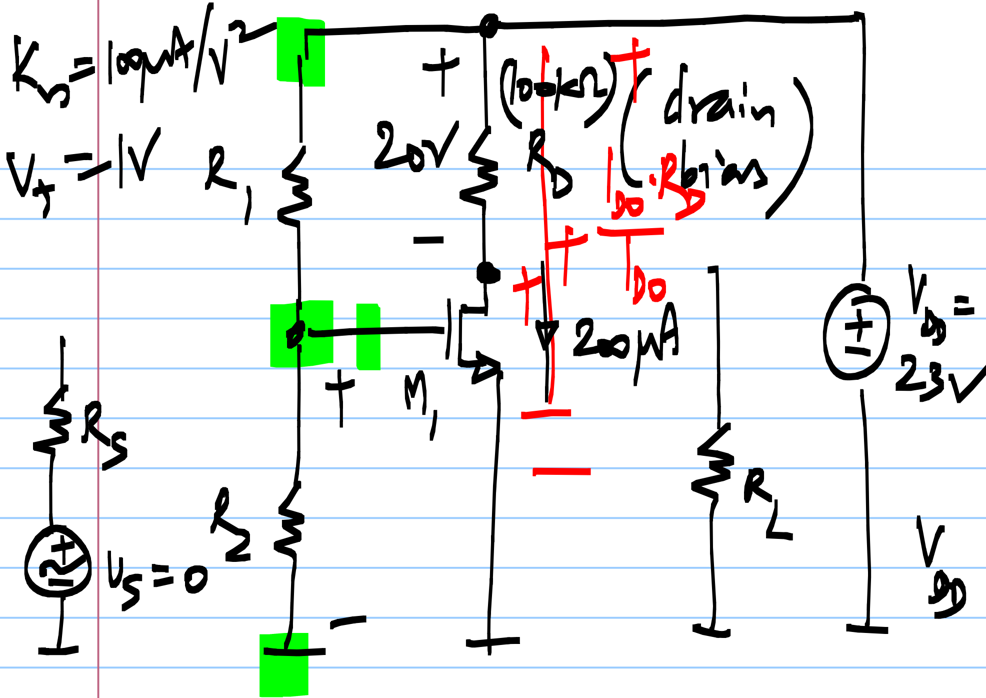
$K_n = \mu_n C_{ox} \frac{W}{L} = 100\mu A/V^2$

$V_T = 1V$

Incremental equivalent circuit



$\underline{\omega_o}$

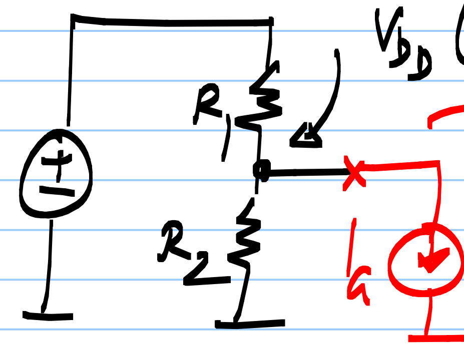


MOS Common source amplifier

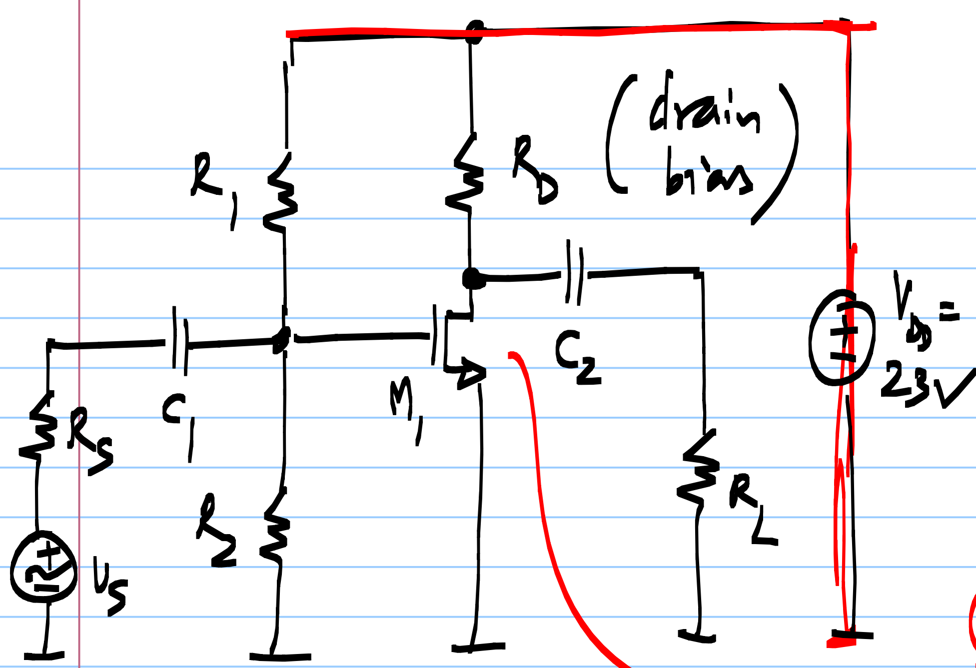
✓ $V_{DS}(=3V) > V_{GS}(3V) - V_T(1V)$

dc operating point:

* signal sources set to zero
* capacitors open circuited
  inductors short circuited



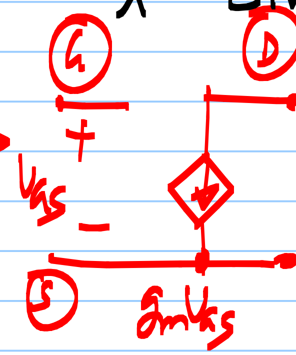
$V_{DD}(R_2/(R_1+R_2))$?



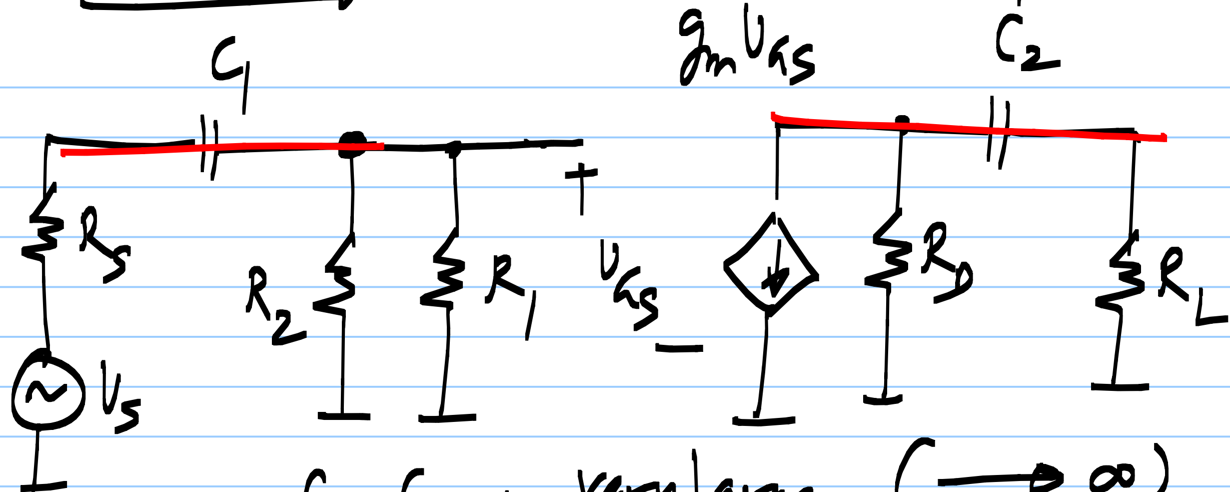
MOS common source amplifier

To obtain small-signal incremental eq. ckt,

* Reduce fixed voltages & currents to zero
* Replace nonlinear elements by small signal equivalents
* Linear elements don't change



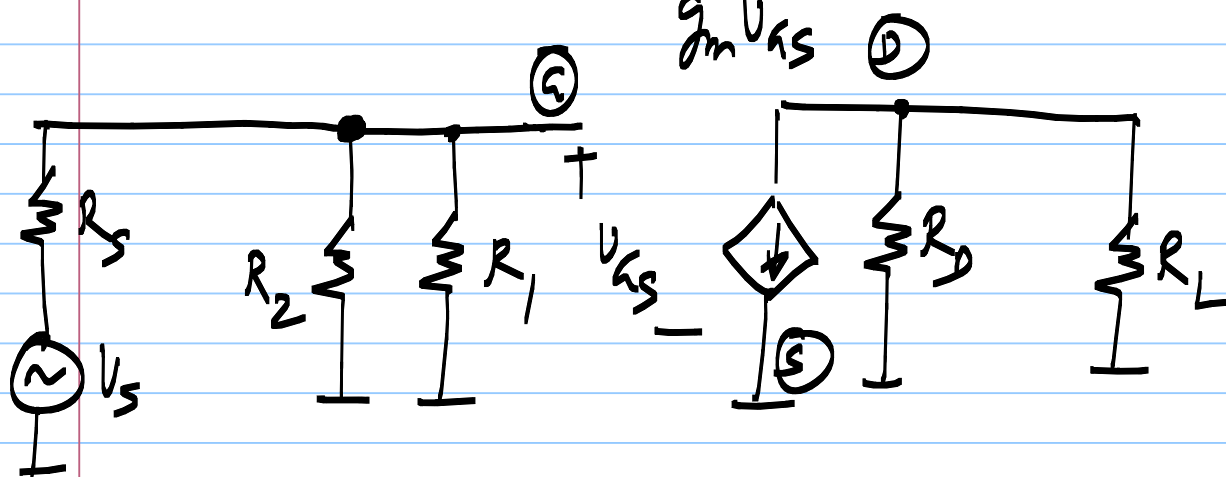
Small signal incremental eq. circuit



C_1, C_2 : very large $(\longrightarrow \infty)$

ω_0 : $\quad \underbrace{\frac{1}{\omega_0 C_1}} \ll (\quad)$; $\quad \underbrace{\frac{1}{\omega_0 C_2}} \ll (\quad)$

Small signal incremental eq. circuit (large capacitors).



COMMON SOURCE AMPLIFIER

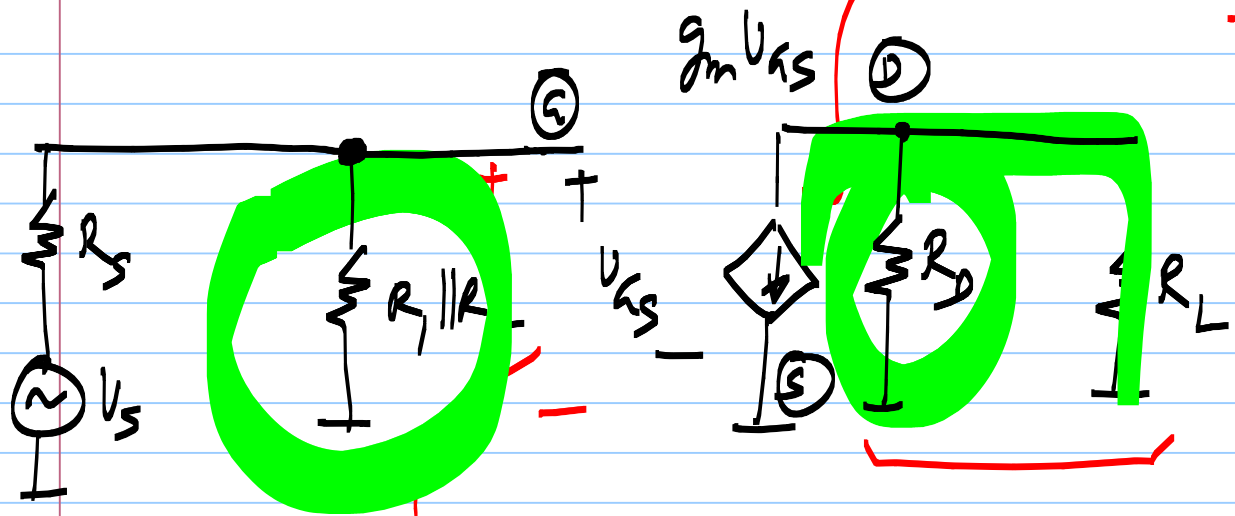
input: gate - source

output: drain - source

CS amplifier

$g_m v_s$

$-(g_m R_L) v_s$



$$+ \quad -g_m (R_D || R_L) \cdot v_s \quad -$$

$$v_s \cdot \left(\frac{R_1 || R_2}{R_1 || R_2 + R_s} \right) \simeq v_s \quad \text{if } R_1 || R_2 \gg R_s$$

$$R_1, R_2 \gg R_s$$

op. point $\quad V_{DS} = \underline{\underline{V_{DD}}} - I_{D_0} \cdot R_D$

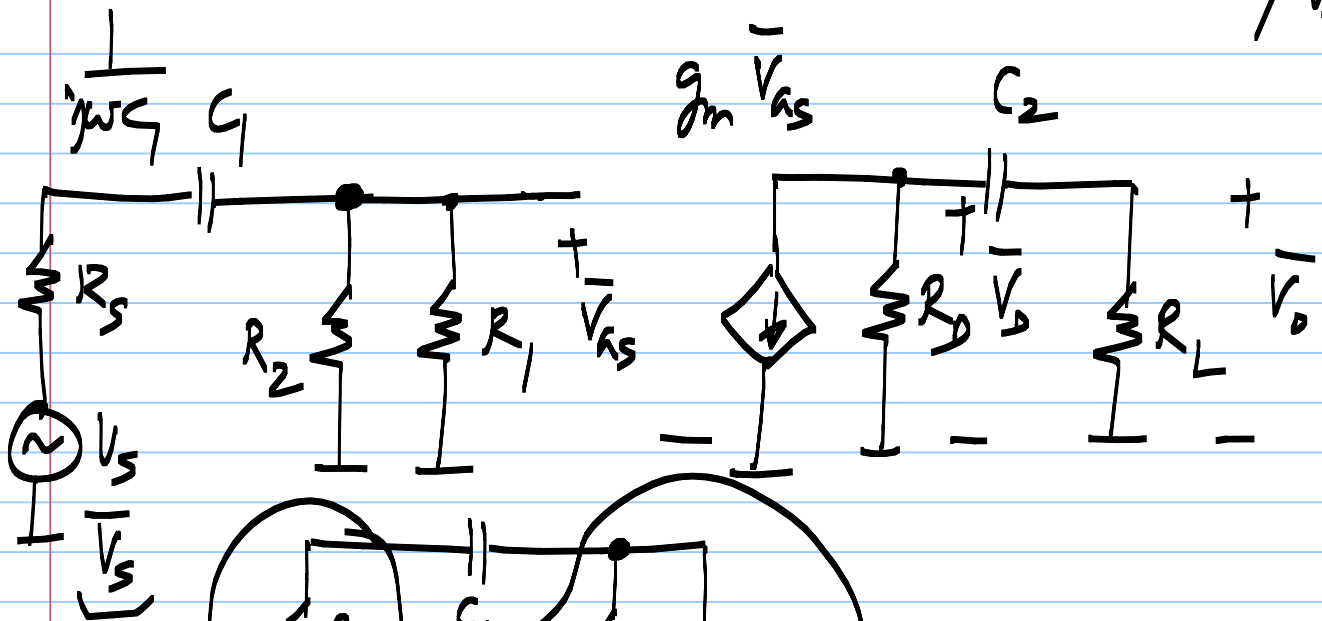
$\underline{V_{DS} > V_{GS} - V_T}$ $\quad \left[V_{DD} = \underline{V_{DS}} + I_{D_0} \cdot R_D \right]$

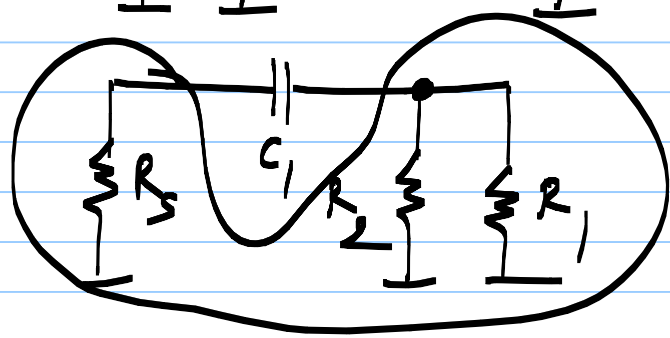
* For a fixed V_{DD}, increasing R_D drives the transistor into triode region

* For a fixed V_{DS}, increasing R_D requires an increase in V_{DD}

ω : frequency of V_s

$\bar{V}_{GS}/\bar{V}_s$; $\bar{V}_o/\bar{V}_{GS}$





$$\frac{\bar{V}_{as}}{\bar{V}_s} = \frac{(R_1 \| R_2)}{R_1 \| R_2 + R_s + \frac{1}{j\omega C_1}} = \frac{j\omega C_1 (R_1 \| R_2)}{1 + j\omega C_1 \left((R_1 \| R_2) + R_s\right)}$$

C_1 : large If $\omega C_1 \left((R_1 \| R_2) + R_s\right) \gg 1$

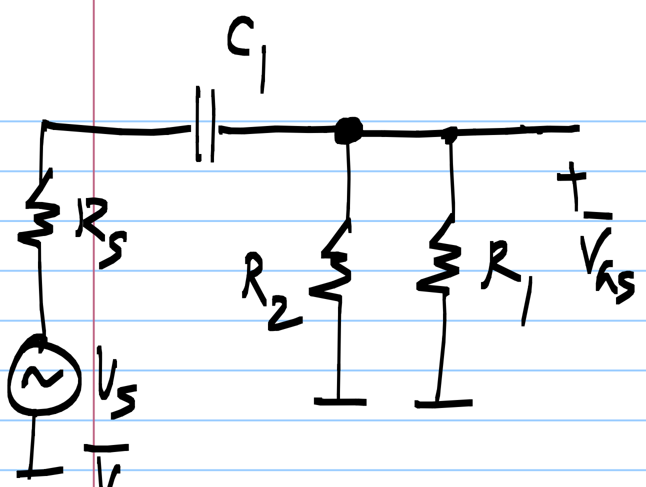
$$\frac{\bar{V}_{as}}{\bar{V}_s} \simeq \frac{R_1 \| R_2}{R_1 \| R_2 + R_s}$$

$$\frac{1}{\omega C_1} \ll (R_1 \| R_2) + R_s$$

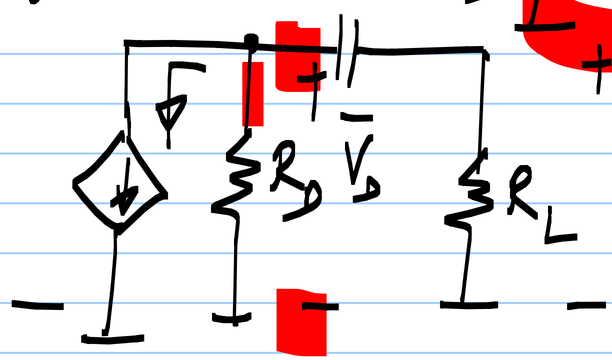
Time constant $\gg$ $(1/\omega)$ rad/s

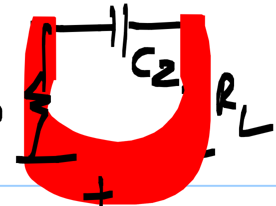
$$C_1 \gg \frac{1}{\underbrace{\omega\left((R_1 \| R_2) + R_S\right)}_{10\,nF}}$$

$$C_1 = 10 \times 10\,nF = 100\,nF$$



$\underbrace{\bar{V}_s}$





$$\frac{1}{\omega C_2} \ll (R_D + R_L)$$

$$\frac{\bar{V}_o}{\bar{V}_{gs}} = -g_m \cdot \frac{R_D}{R_D + R_L + \frac{1}{j\omega C_2}} \cdot R_L$$

$$-g_m \cdot \frac{j\omega C_2 (R_D R_L)}{+ \underbrace{j\omega C_2 (R_D + R_L)}}$$

$$\omega C_2 (R_D + R_L) \gg 1$$

$$\frac{V_D}{V_{gs}} = -g_m \cdot \frac{R_D \cdot \left(R_L + \frac{1}{j\omega C_2}\right)}{R_D + R_L + \frac{1}{j\omega C_2}} = -g_m \frac{R_D\left(1 + j\omega C_2 R_L\right)}{1 + j\omega C_2 (R_D + R_L)}$$

$\omega C_2 R_L \gg 1$ ✓

$\omega C_2 (R_D + R_L) \gg 1$ ✓

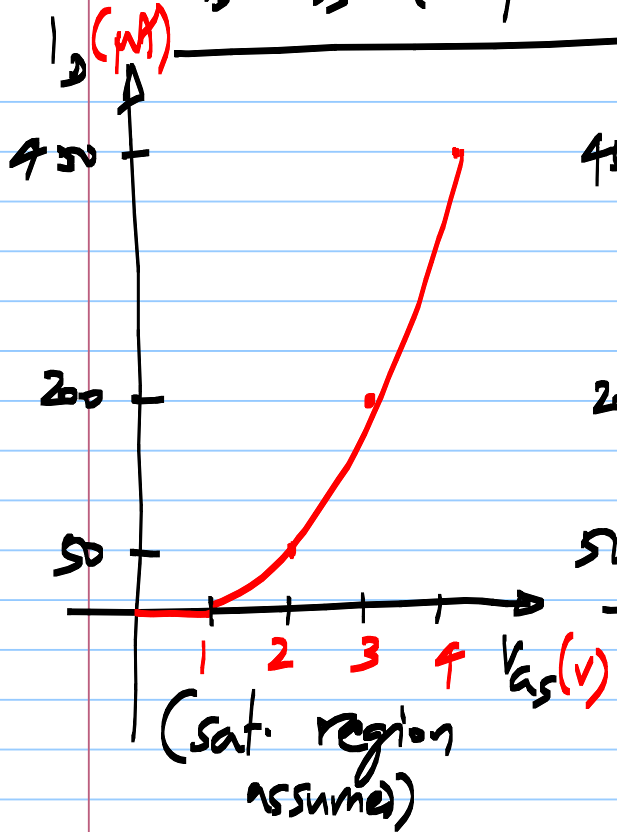
$\omega C_2 R_L \gg 1$ [Drain-source signal voltage = output voltage]

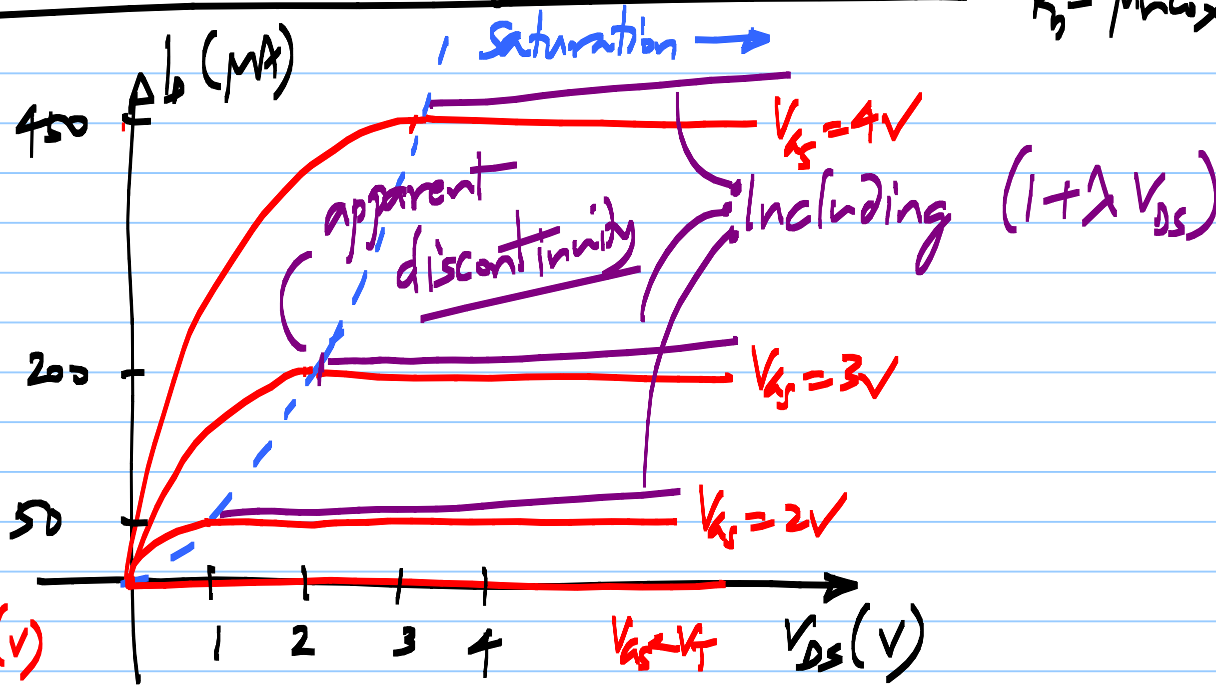
* Consider one capacitor at a time
* Assume all other capacitors are shorts

only first order circuits

$I_D - V_{DS}$ (output) characteristics of the MOS transistor

$V_T = 1V$, $k_n = \mu_n C_{ox} \frac{W}{L} = 100 \mu A/V^2$





Current increases (roughly) with V_{DS} in saturation region

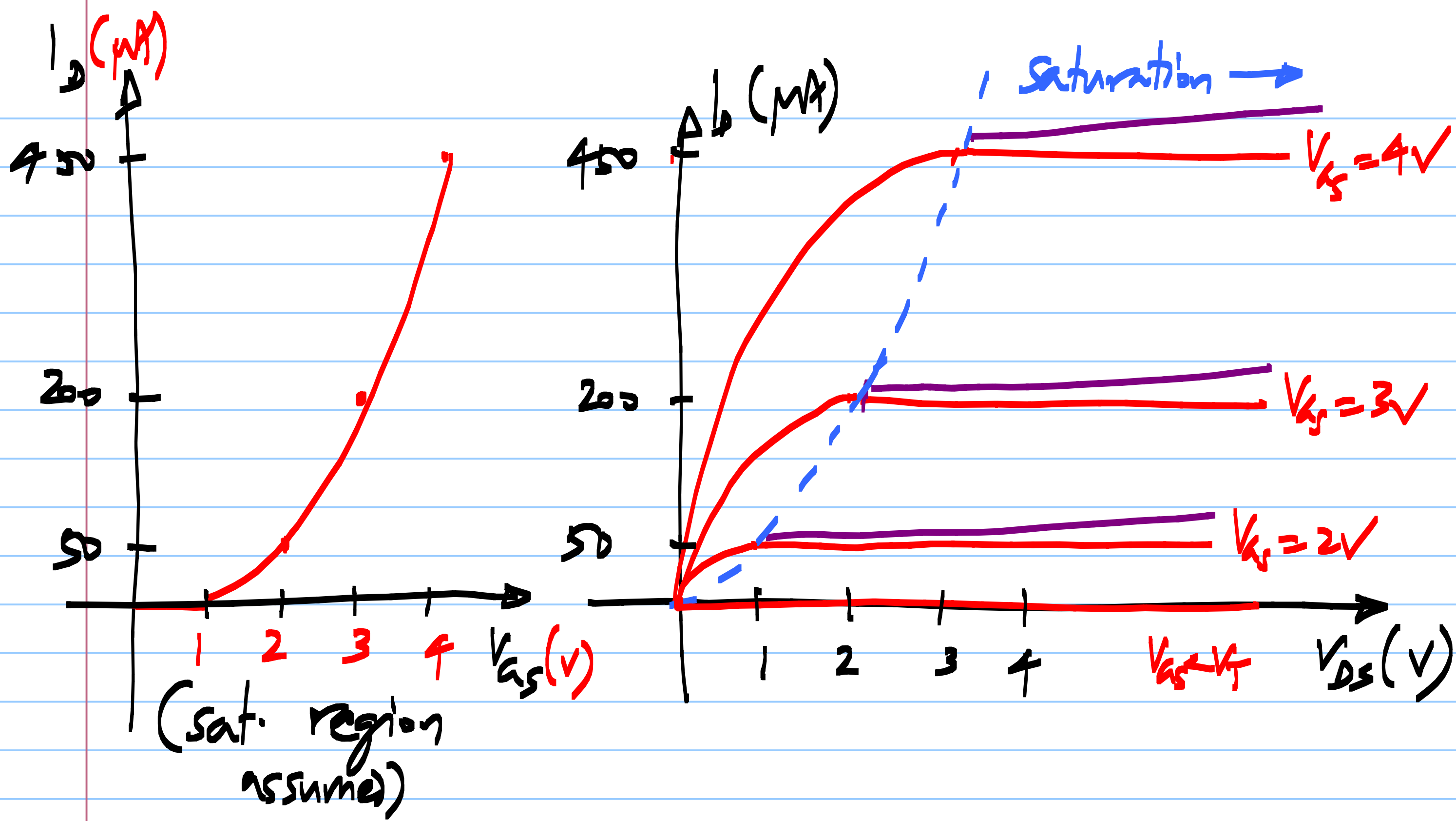
$$I_D = \frac{\mu_n C_{ox}}{2} \frac{W}{L} (V_{GS} - V_T)^2 (1 + \lambda V_{DS}) \qquad V_{DS} > V_{GS} - V_T$$

$$\lambda = 0.05\,V^{-1}$$

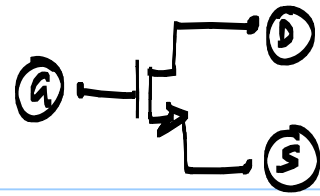
channel length modulation

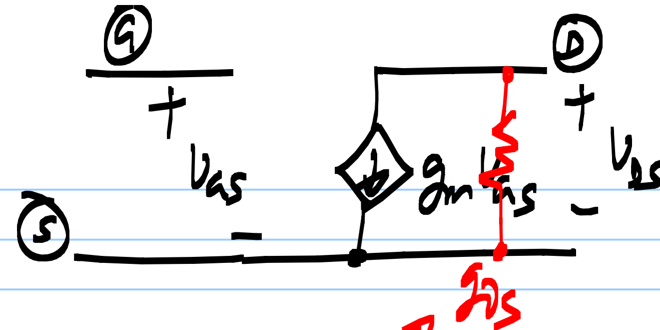
$$\lambda = \frac{k_\lambda}{L}$$

λ: inversely varies as transistor length



I_D (μA)
450
200
50
1
2
3
4
V_GS (V)
(sat. region assumed)
I_D (μA)
450
200
50
Saturation
V_GS = 4V
V_GS = 3V
V_GS = 2V
1
2
3
4
V_GS < V_T
V_DS (V)





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

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T)(1 + \lambda V_{DS})$$

$$g_{ds} = \frac{\partial I_D}{\partial V_{DS}} = \lambda \cdot \frac{\mu_n C_{ox}}{2} \cdot \frac{W}{L} (V_{GS} - V_T)^2$$

non-zero
drain-source
conductance

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

For op. point calculations $1 + \lambda V_{DS}$ ignored

$$g_m = \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_T) \cancel{(1 + \lambda V_{DS})}$$

$$g_{ds} = \lambda \cdot \underbrace{\frac{\mu_n C_{ox}}{2} \frac{W}{L} (V_{GS} - V_T)^2}_{I_D} \simeq \underline{\lambda \cdot I_D}$$

$V_T = 1V$, $\mu_n C_{ox} \frac{W}{L} = 100\mu A/V^2$

$\lambda = 0.05 V^{-1}$

$V_{GS} = 3V$

$\lambda = 0$

$V_{DS} = 3V$

$\downarrow$

saturation

$I_D = 200\mu A(1 + \underbrace{\lambda \cdot V_{DS}}_{0.15})$

$230\mu A$

$g_m = 200\mu S(1 + \underbrace{\lambda V_{DS}}_{0.15})$

$230\mu S$

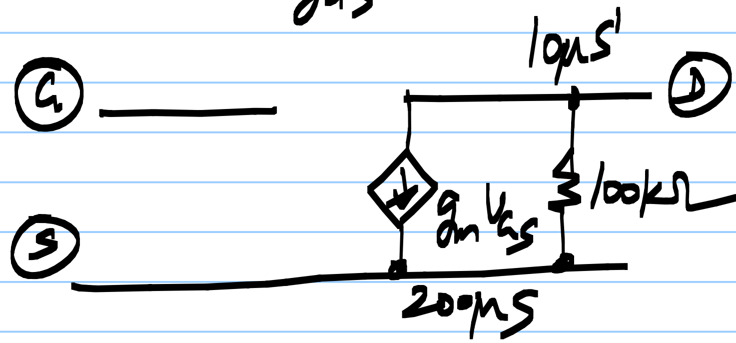
$g_{ds} = \lambda \cdot 200\mu A$

$= 10\mu S$

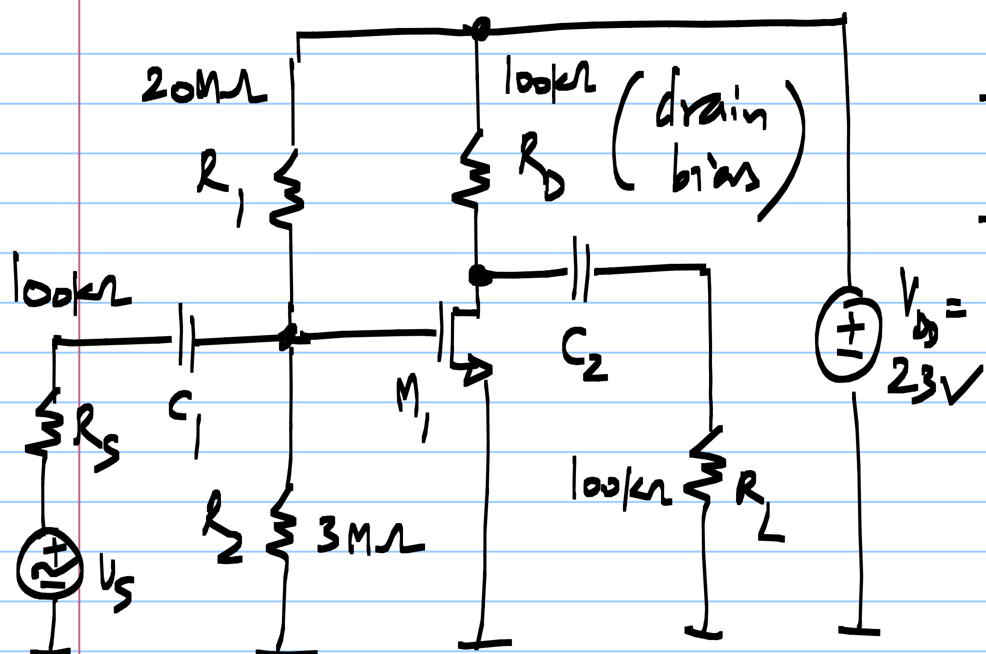
$I_D = 200\mu A$

$g_m = 200\mu S$

$g_{ds} = 0$



Effect of g_{ds} on the CS amplifier



$V_{GS} = 3V$, $V_{DS} = 3V$, $I_D = 200\mu A$

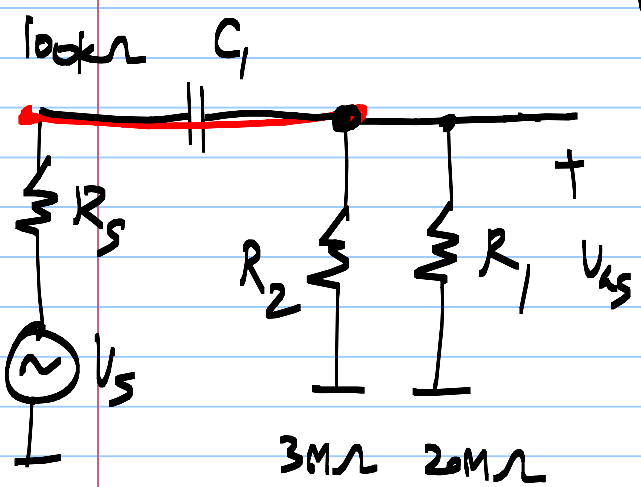
$g_m = 200\mu S$

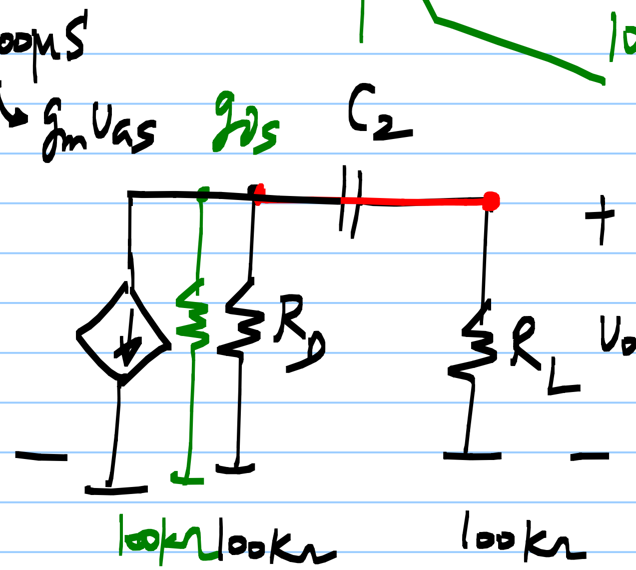
C_1, C_2: very large ; $R_1, R_2 \gg R_s$

$g_{ds} \simeq \underbrace{\lambda I_D}$ $\quad \lambda = 0.05\ V^{-1}$

$= 10\mu S = \dfrac{1}{100k\Omega}$

$r_{ds} = 100k\Omega$
$= 1/g_{ds}$





$-g_m R_L = -20$

$-g_m(R_D||R_L) = -10$

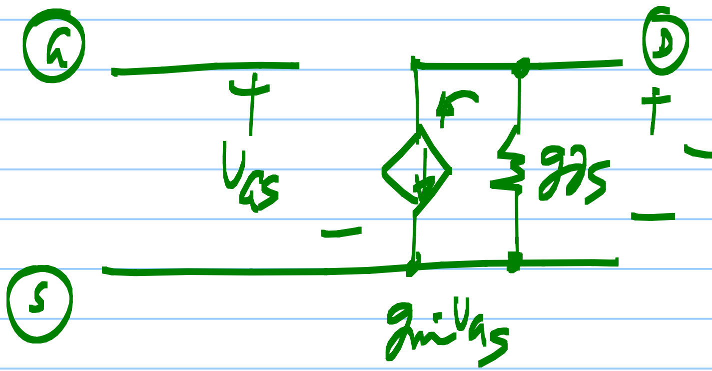
$-g_m(r_{ds}||R_D||R_L) = \underline{-6.7}$

$$\frac{v_o}{v_s} = -g_m(R_D||R_L)$$

$$\frac{v_o}{v_{gs}} = -g_m\underbrace{(r_{ds}||R_D||R_L)}$$

$$\left|\frac{v_o}{v_s}\right| = +g_m\left(R_D \,\|\, R_L \,\|\, r_{ds}\right) < \underline{\underline{g_m \cdot r_{ds}}}$$

→ Inherent gain limit of a transistor



$$-\frac{g_m}{g_{ds}} \cdot v_{gs} = -\underbrace{g_m r_{ds}} \cdot v_{gs}$$