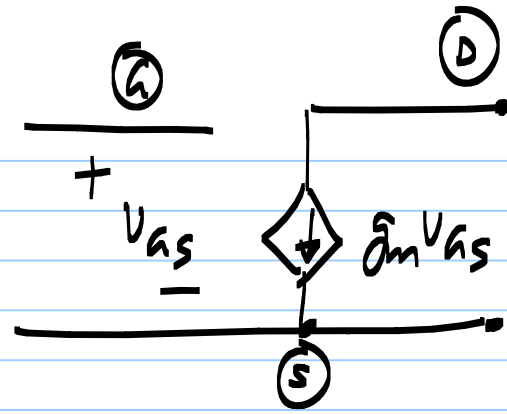
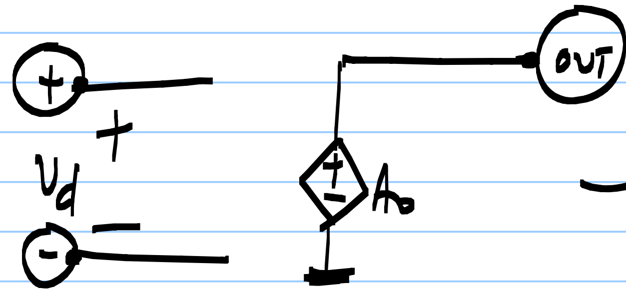
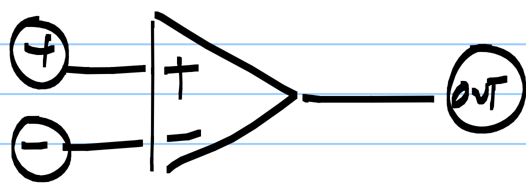
MOS:



VCVS





VCVS & CCVS using negative fb.

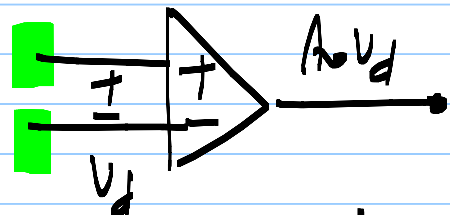
& this device — an opamp

VCVS

$$v_o = k \cdot v_i$$

Error: $k v_i - v_o$

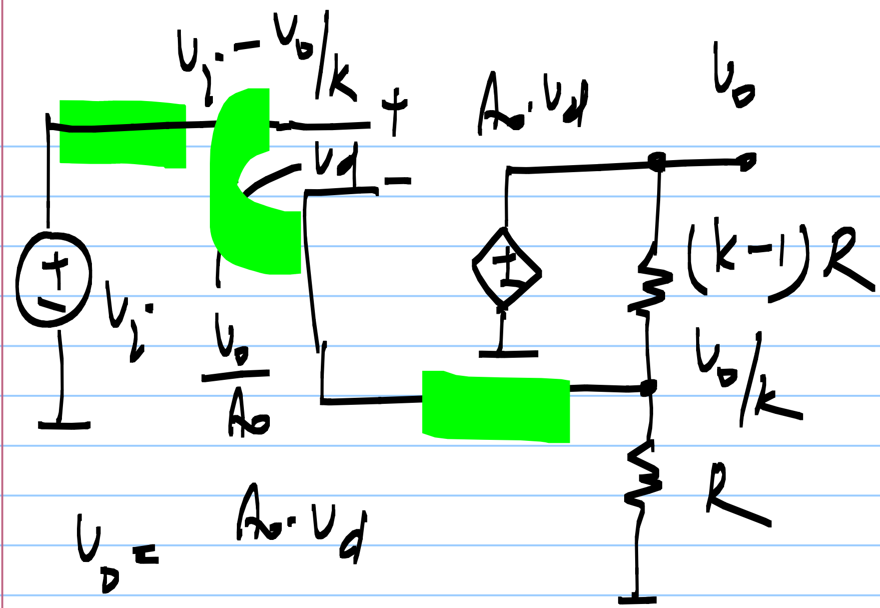
$$v_i - \frac{v_o}{k}$$



$v_d > 0$: o/p large positive

$v_i - \frac{v_o}{k} > 0$ output must be increased

$v_i - \frac{v_o}{k} < 0$ output must be decreased



$$v_o = A_o \cdot v_d$$

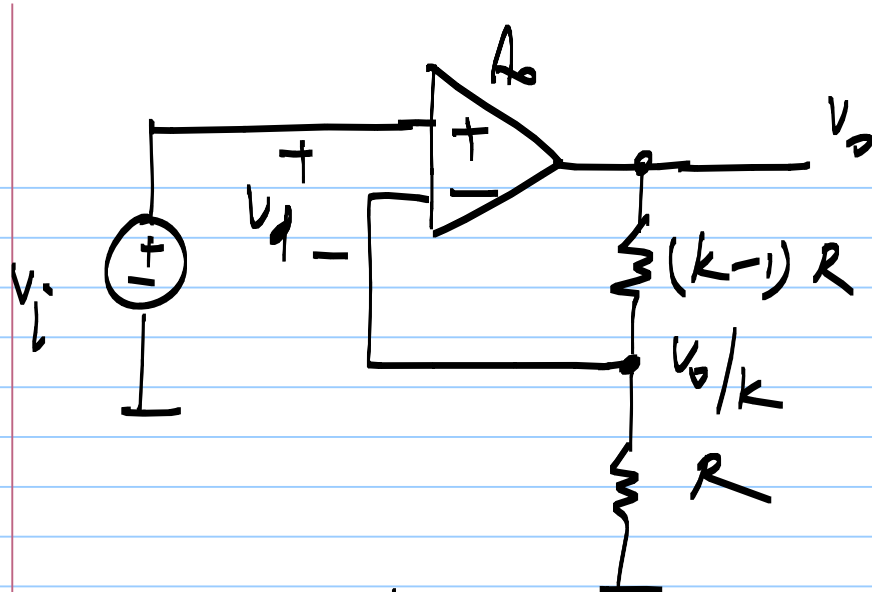
$$v_d = \frac{v_o}{A_o}$$

$$v_i - \frac{v_o}{A_o} = \frac{v_o}{k}$$

$$\frac{v_o}{v_i} = \frac{1}{\frac{1}{A_o} + \frac{1}{k}} = \frac{k}{1 + k/A_o}$$

$$= \frac{A_o}{1 + \frac{A_o}{k}}$$

$\frac{v_o}{v_i} \simeq k$: $\frac{A_o}{k}$: very large



$k = 10$

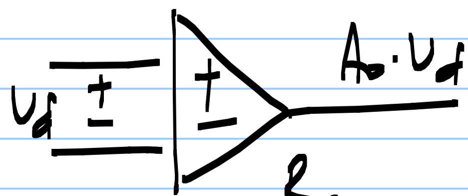
$A_0 = 1000 \rightarrow 2000$

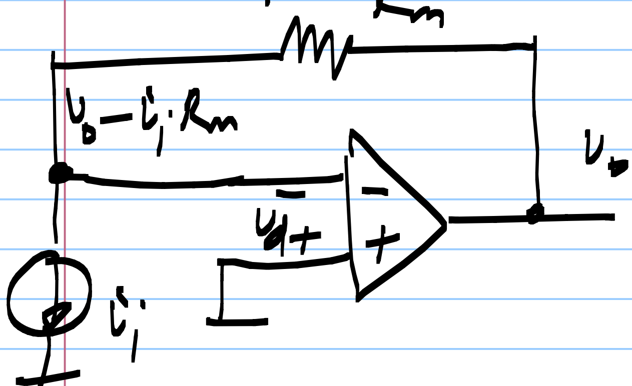
$$\frac{v_o}{v_i} = \frac{10}{1 + \frac{10}{\cancel{1000}\ 2000}} \simeq 10\underbrace{(0.99)}_{0.995} = 9.9 \quad 9.95$$

$$\frac{v_o}{v_i} = \frac{k}{1 + \frac{k}{A_0}} \simeq k \quad \text{if} \quad \underline{\frac{A_0}{k} \gg 1}$$

· CCVS using an opamp.

$v_o = i_i \cdot R_m$





$v_o - i_i \cdot R_m > 0$, output must be reduced

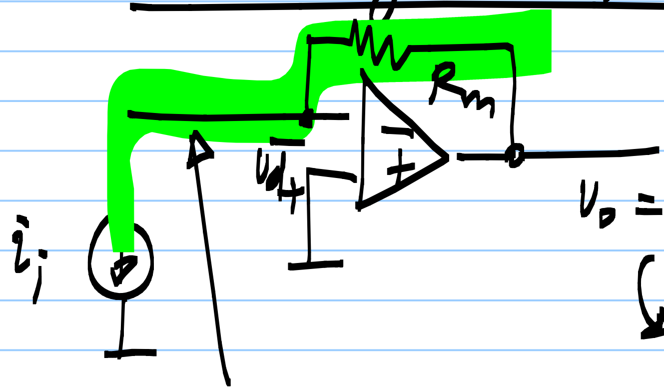
$v_o - i_i \cdot R_m < 0$, output must be increased

$\underbrace{\phantom{v_o - i_i \cdot R_m < 0}}$

$v_d > 0$

$v_d = -(v_o - i_i \cdot R_m)$

CCVS using an opamp:

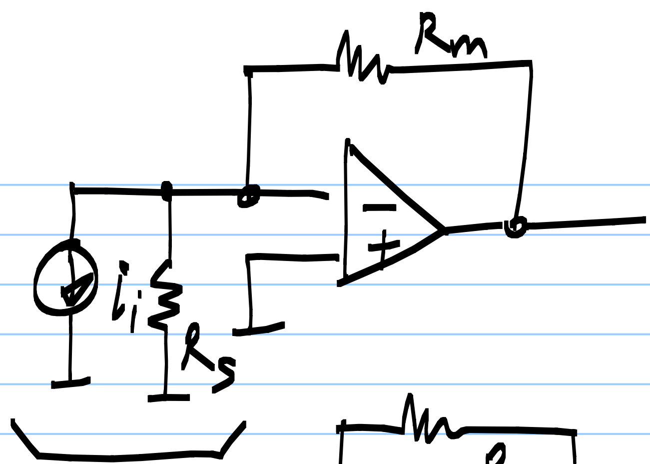


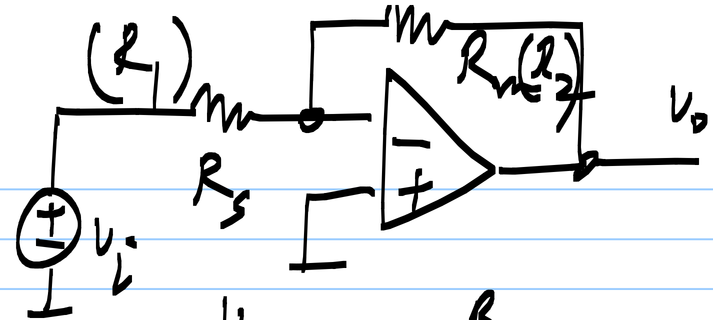
$v_o = A_o v_d$

$\Rightarrow v_d = v_o / A_o$

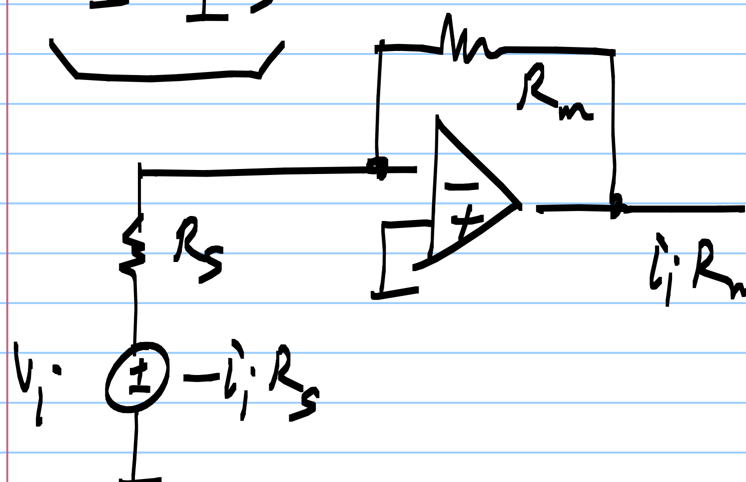
$v_o - i_i R_m = -v_d = \dfrac{v_o}{A_o}$

$$\frac{v_o}{i_i} = \frac{R_m}{1 + \frac{1}{A_o}} \simeq R_m \quad \text{if } A_o \to \infty$$



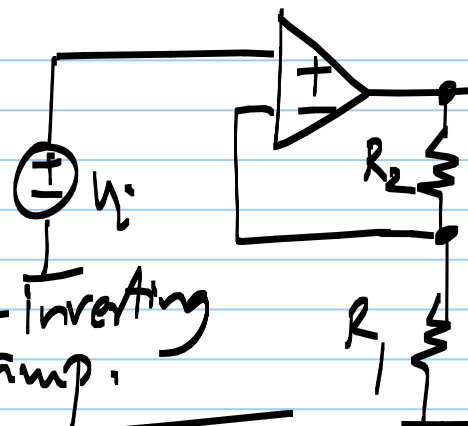


$$\frac{v_o}{v_i} = -\frac{R_m}{R_s} = -\frac{R_2}{R_1}$$



$$i_i R_m = -v_i \frac{R_m}{R_s}$$

VCVS



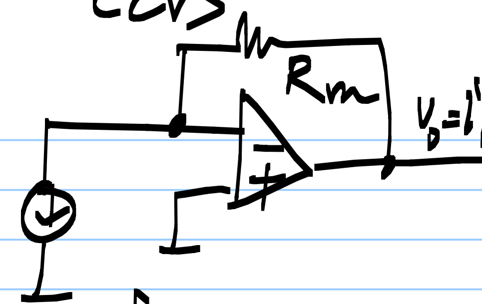
$v_o = k v_i = \left(1 + \frac{R_2}{R_1}\right) v_i$ if $A_o \to \infty$

$R_2 = (k-1)R$

$R_1 = R$

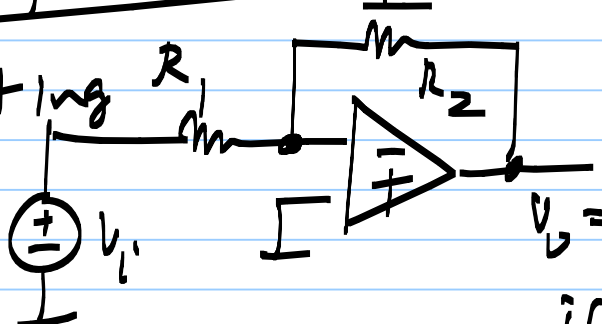
Non-Inverting amp.

CCVS



$v_o = i_i R_m$ if $A_o \to \infty$

Inverting amp.



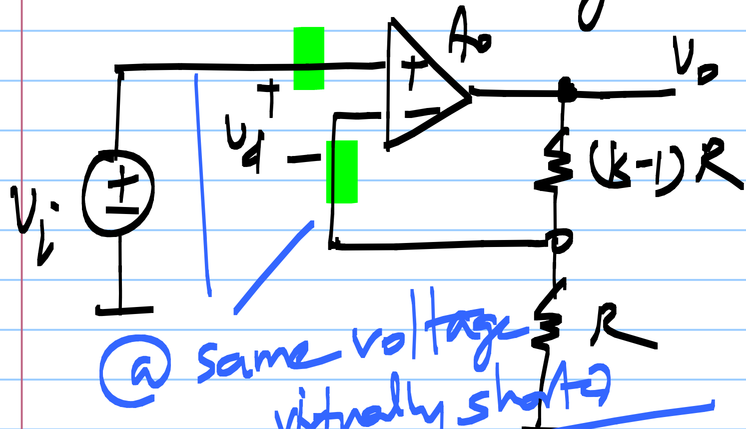
$v_o = -\frac{R_2}{R_1} \cdot v_i$ if $A_o \to \infty$

Negative feedback and virtual short

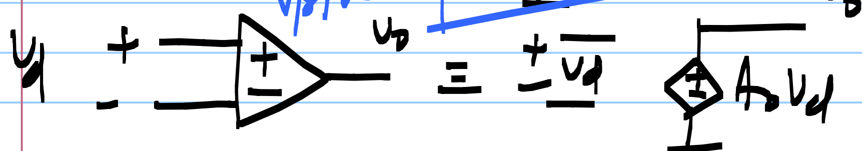
$$v_o = v_i \cdot \frac{k}{1 + k/A_o} \rightarrow k \quad \text{as } A_o \rightarrow \infty$$

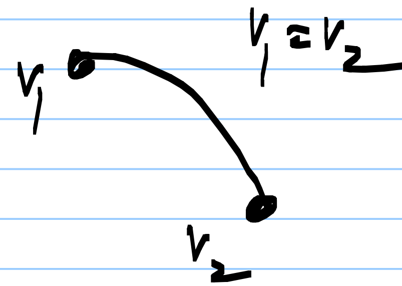
VCVS - Non-inverting amplifier

$$v_d = \frac{v_o}{A_o} = v_i \cdot \frac{k/A_o}{1 + k/A_o}$$

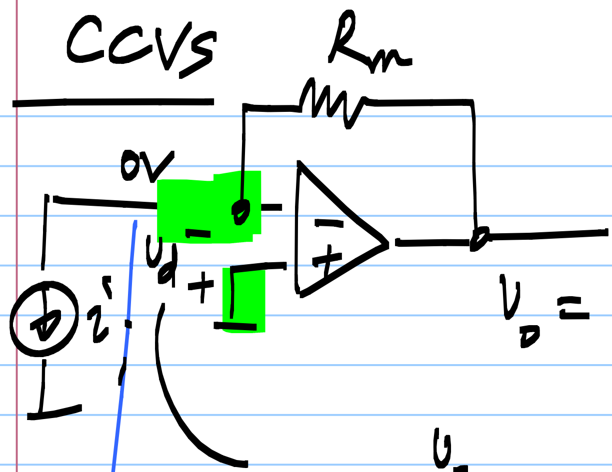


$$v_d \rightarrow 0 \quad \text{as } A_o \rightarrow \infty$$





CCVS

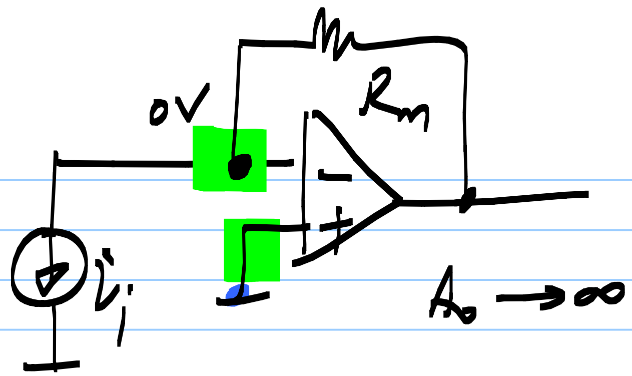


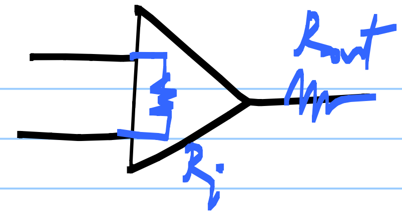
$$v_o = \frac{i_i R_m}{1 + 1/A_o}$$

$$v_d = \frac{v_o}{A_o} = i_i \frac{R_m / A_o}{1 + 1/A_o}$$

virtual ground

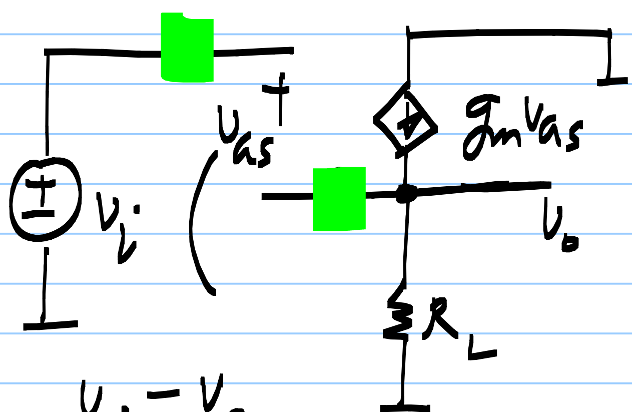
$v_d \rightarrow 0$ as $A_o \rightarrow \infty$


0V
R_m
i_i
$A_o \rightarrow \infty$


R_{out}
R_i

Virtual short in circuits with transistors in -ve feedback

Source follower



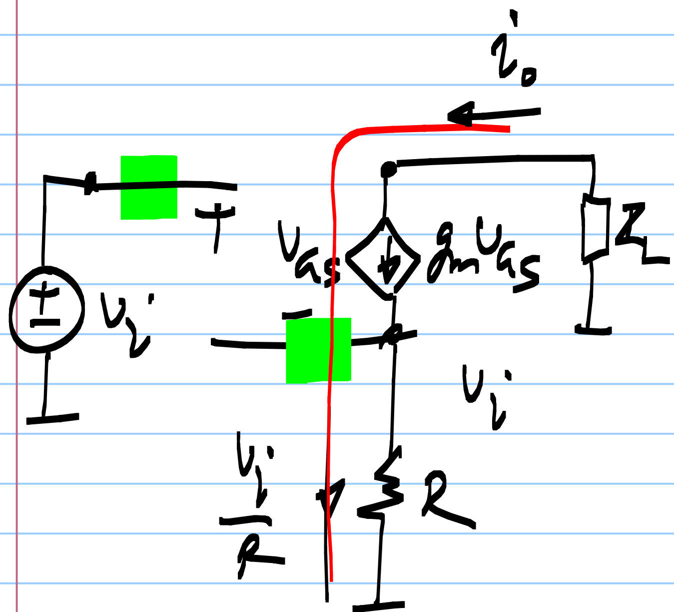
$v_i - v_o$

$$v_o = v_i \cdot \frac{g_m R_L}{1+g_m R_L} \; ; \; v_{gs} = \frac{1}{1+g_m R_L}$$

$g_m R_L \rightarrow \infty$: $\underline{v_{gs} \rightarrow 0}$

Virtual short between gate and source

VCCS

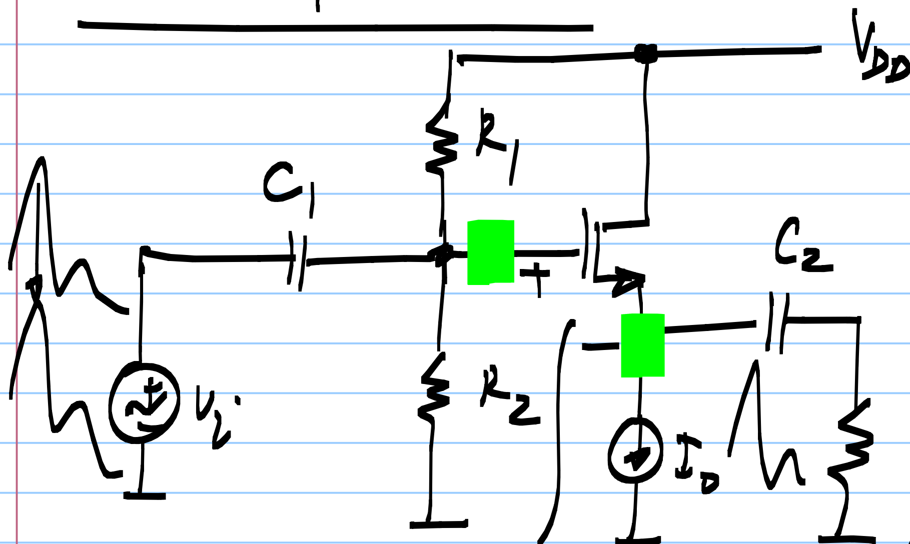


$$i_o = v_i \cdot \frac{g_m}{1+g_m R} \simeq v_i \cdot \frac{1}{R} \text{ if } g_m R \to \infty$$

$$v_{GS} = v_i \cdot \frac{1}{1+g_m R} \longrightarrow 0 \text{ as } g_m R \to \infty$$

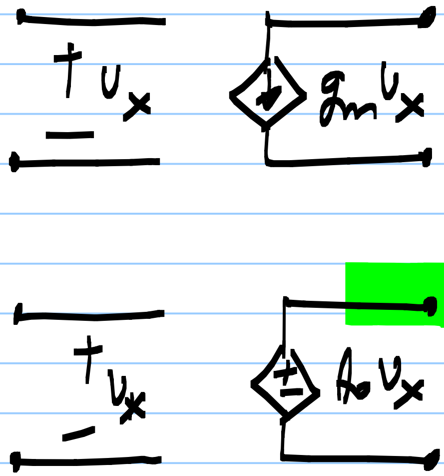
Source follower

Incremental $V_{GS} = 0$ if $g_m R_L \to \infty$



op. point $V_{GS} = V_T + \sqrt{\dfrac{2 I_D}{\mu_n C_{ox} W/L}}$

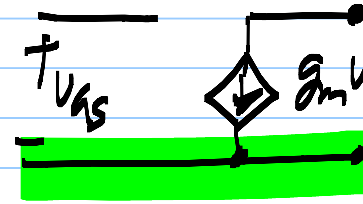
Transistor		Opamp	
VCVS	$v_o = v_i$	VCVS	$v_o = k v_i$
VCCS			
CCCS	$i_o = i_i$		
CCVS		CCVS	



with any gain

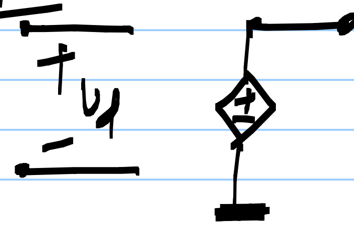
Using these any controlled source can be built using negative feedback

MOS



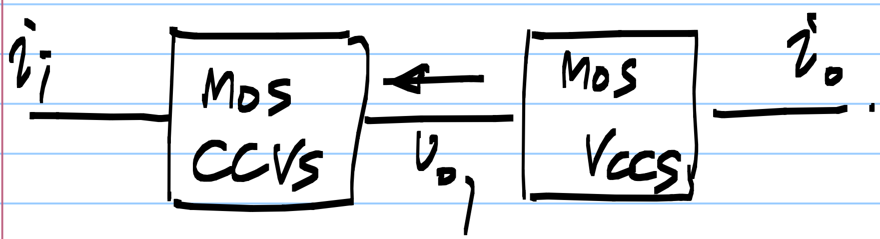
$\Rightarrow$ VCVS, CCCS: gain = 1

OPAMP



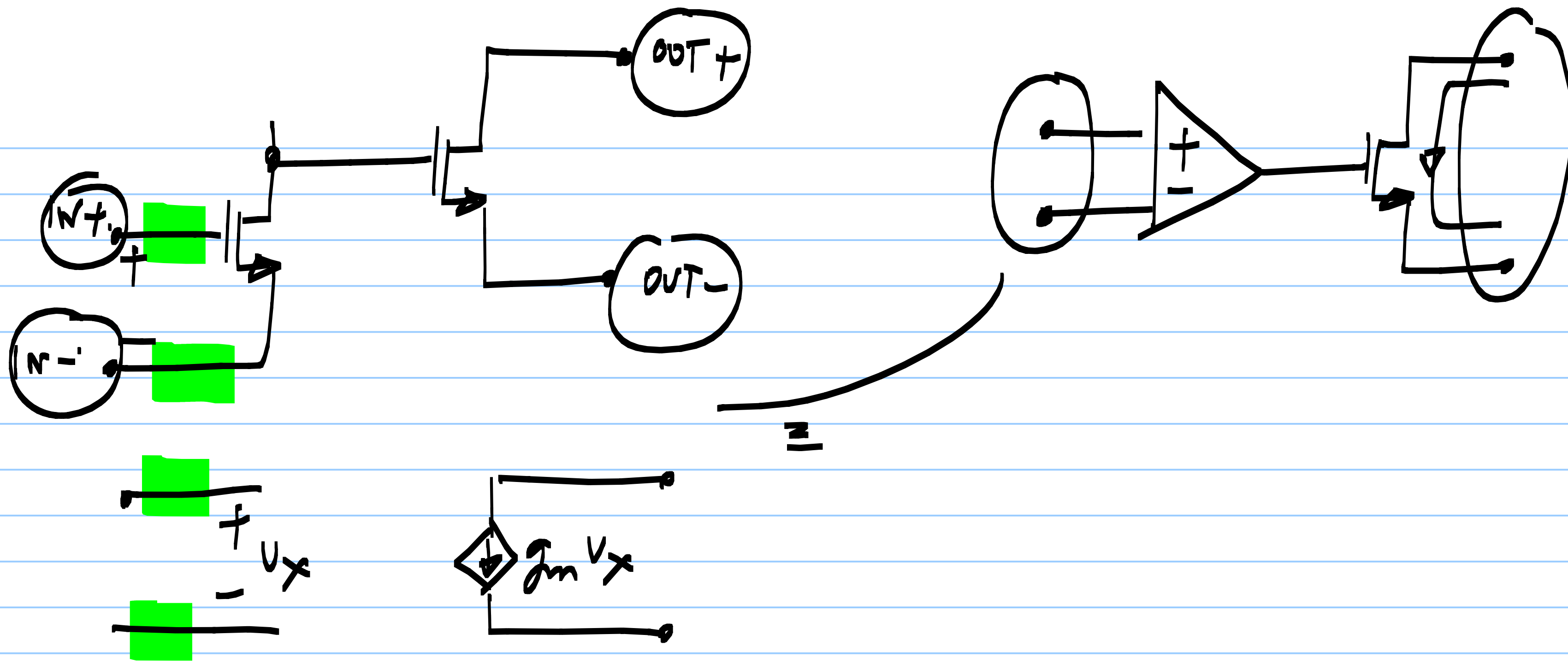
~~CCCS~~, ~~VCCS~~

MOS $\underline{\text{VCVS, CCCS} \quad k > 1 \ ?}$



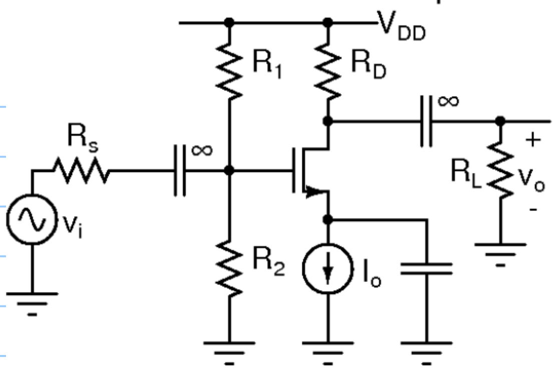
$i_{o_1} = G_m \cdot v_i$; $\quad v_o = R_m' \cdot i_{o_1}$

$$v_o = \underbrace{G_m \cdot R_m'}_{> 1} v_i$$

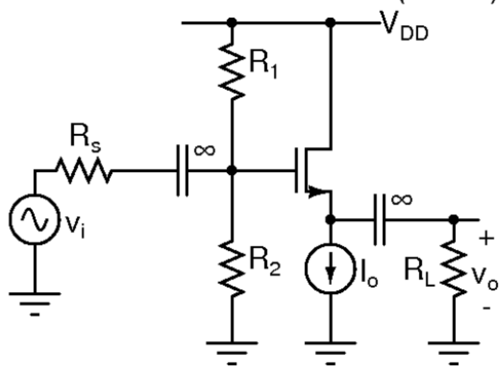


IN+
IN-
OUT+
OUT-
+
-
v_x
$g_m v_x$

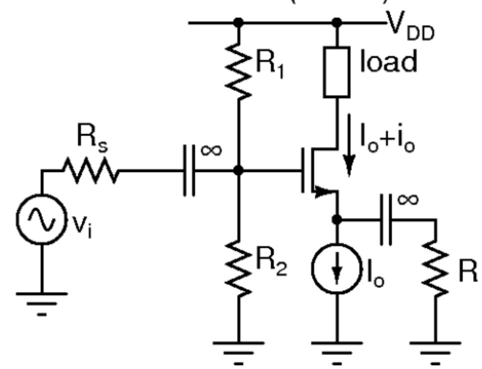
Common Source Amplifier



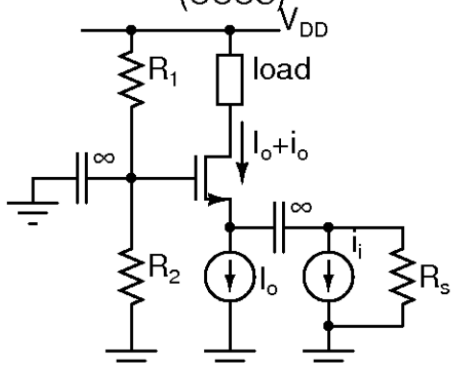
Common Drain Amplifier
Source Follower (VCVS)



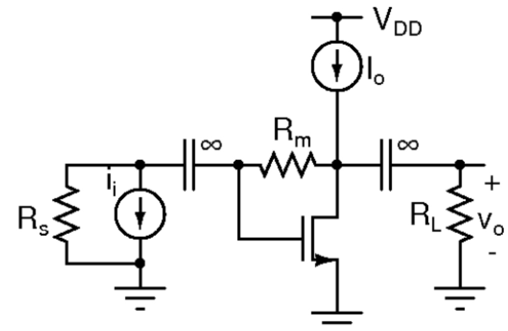
Source Degeneration
(VCCS)



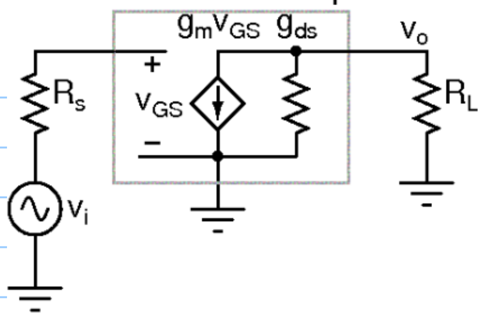
Common Gate Amplifier
(CCCS)



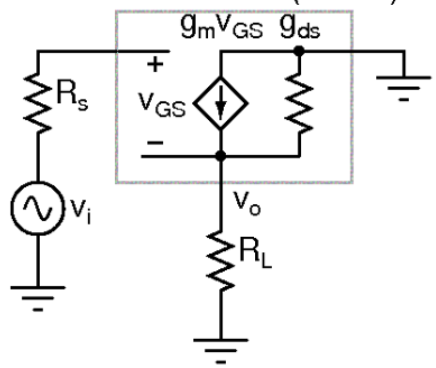
Drain Feedback Amplifier
(CCVS)



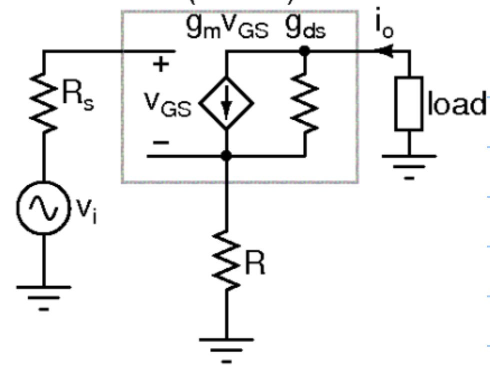
Common Source Amplifier



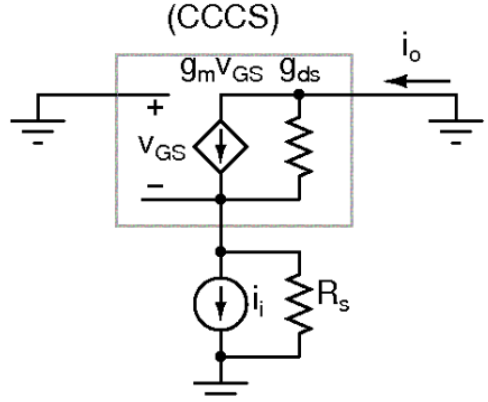
Common Drain Amplifier
Source Follower (VCVS)



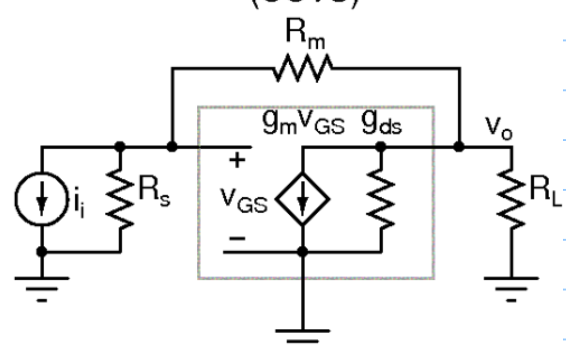
Source Degeneration
(VCCS)



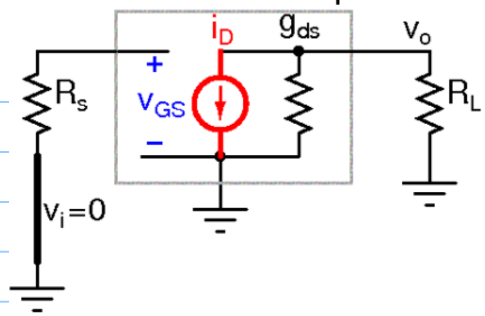
Common Gate Amplifier
(CCCS)



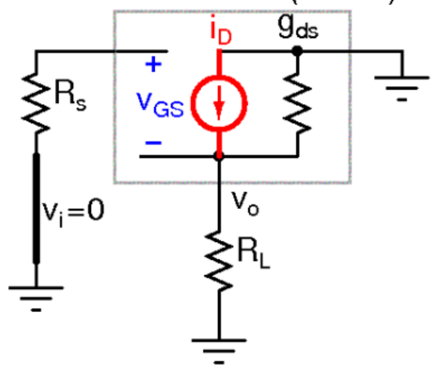
Drain Feedback Amplifier
(CCVS)



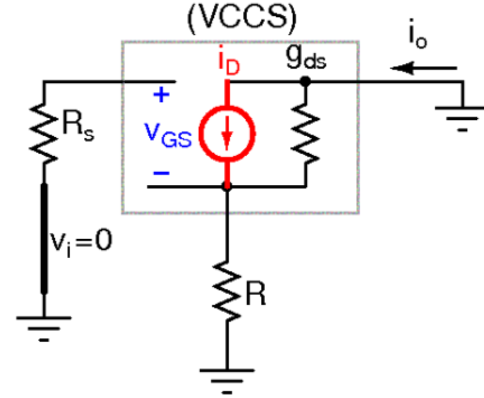
Common Source Amplifier



Common Drain Amplifier
Source Follower (VCVS)



Source Degeneration
(VCCS)

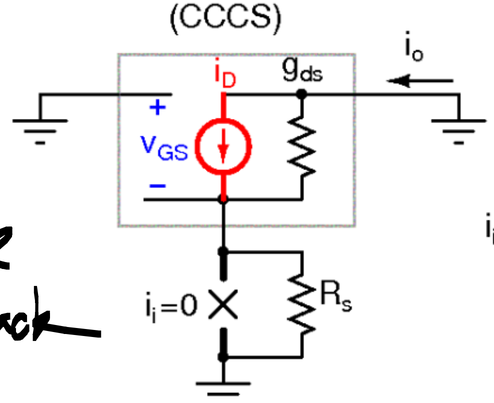


$$\underbrace{V_{GS} = (\alpha)}_{\text{feedback}} \cdot i_D$$

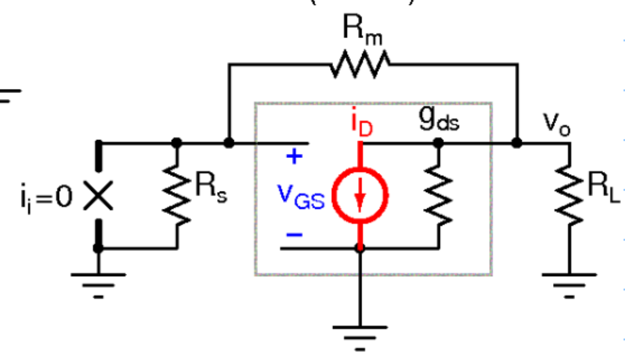
$\alpha \neq 0 \Rightarrow$ feedback

$\alpha < 0 \Rightarrow$ negative feedback

Common Gate Amplifier
(CCCS)



Drain Feedback Amplifier
(CCVS)



Amplifiers (or any other electronic circuit)

* Maximum input amplitude is limited by nonlinearity

$V_p \cos \omega t$ —— $\boxed{\text{Linear}}$ —— $\underbrace{V_{op}\cos(\omega t + \phi)}$

$\quad$ —— $\boxed{\text{Nonlinear}}$ —— $V_{op}\cos(\omega t + \phi)$

nonlinear products
$$\left[\begin{array}{l} + V_{o2p}\cos(2\omega t + \phi_2) \\ + V_{o3p}\cos(3\omega t + \phi_3) \end{array}\right.$$

Swing limits of amplifiers

→ Limits on input (or output) such that transistors remain in saturation region

CS amplifier

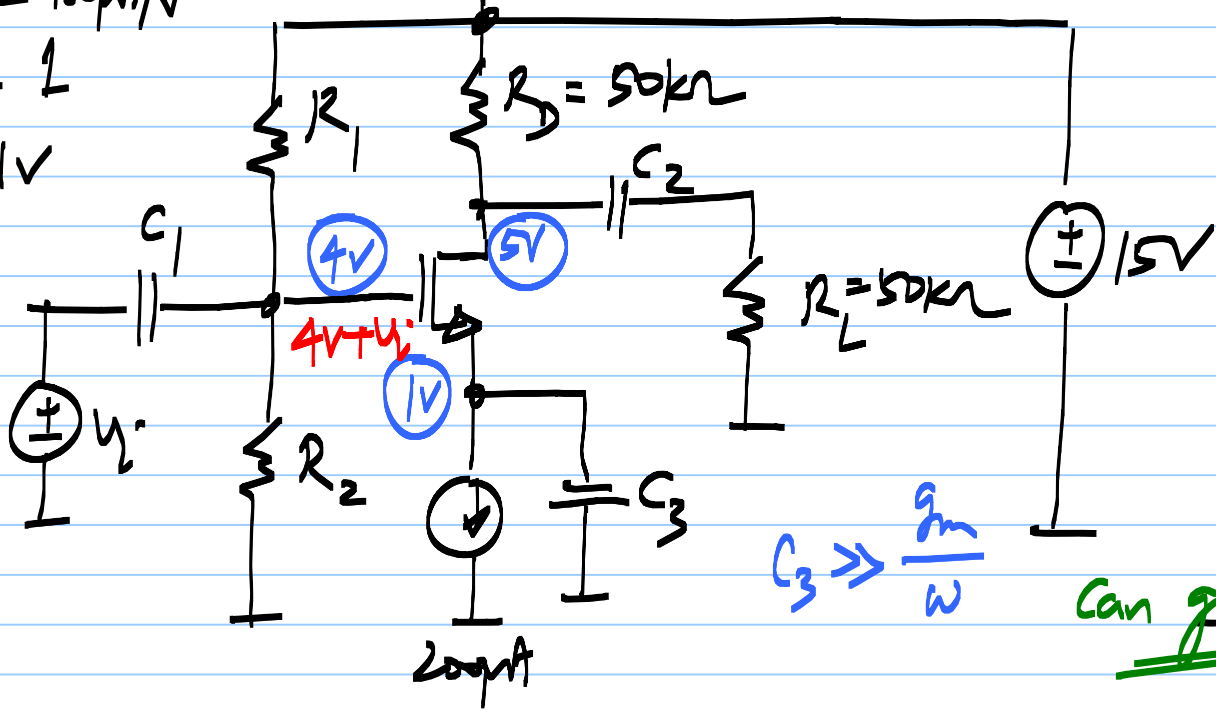
$\mu_n C_{ox} = 100\mu A/V^2$

$W/L = 1$

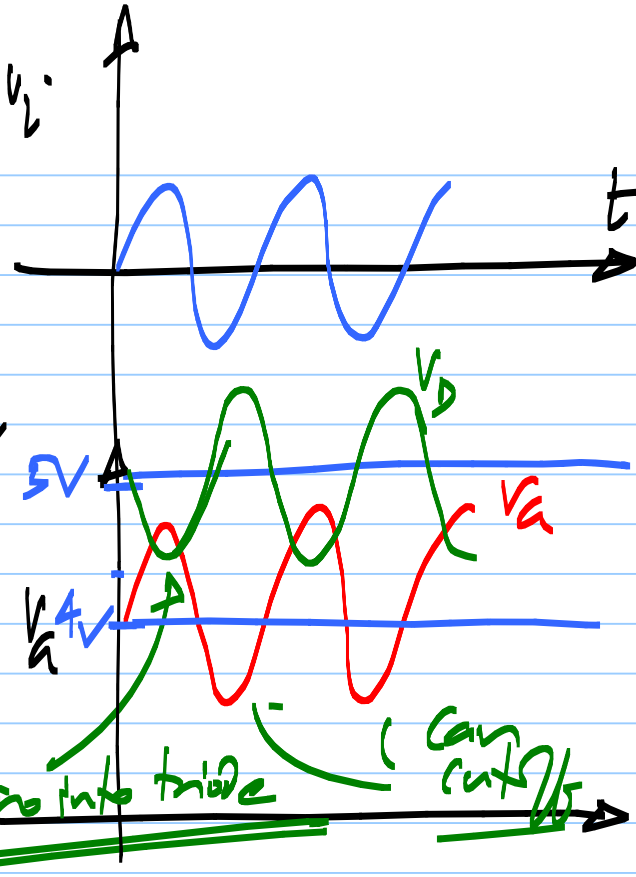
$V_T = 1V$

$$\frac{R_2}{R_1+R_2} = \frac{4}{15}$$

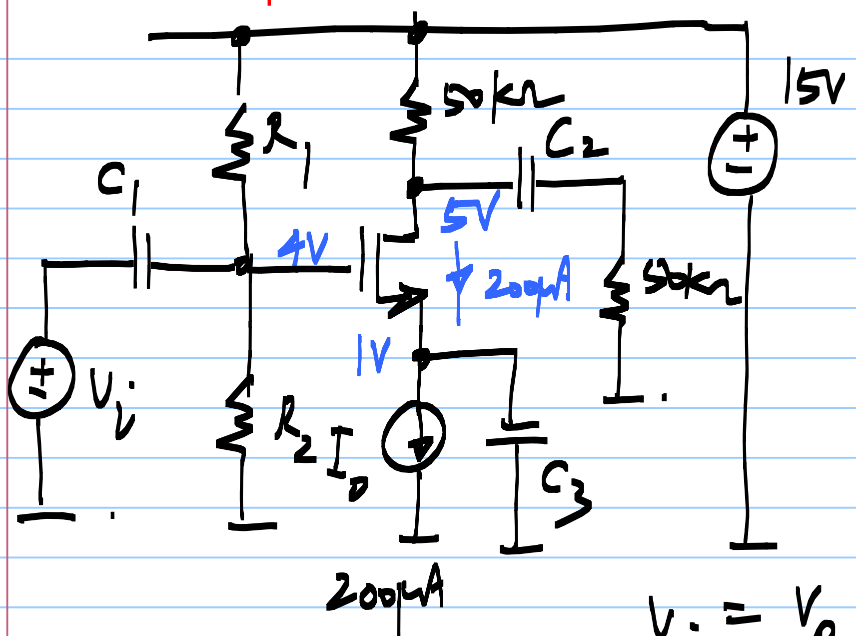
$-g_m(R_D \| R_L)v_i$



$C_3 \gg \frac{g_m}{\omega}$



$-200\mu S\,(25k\Omega) = -5$



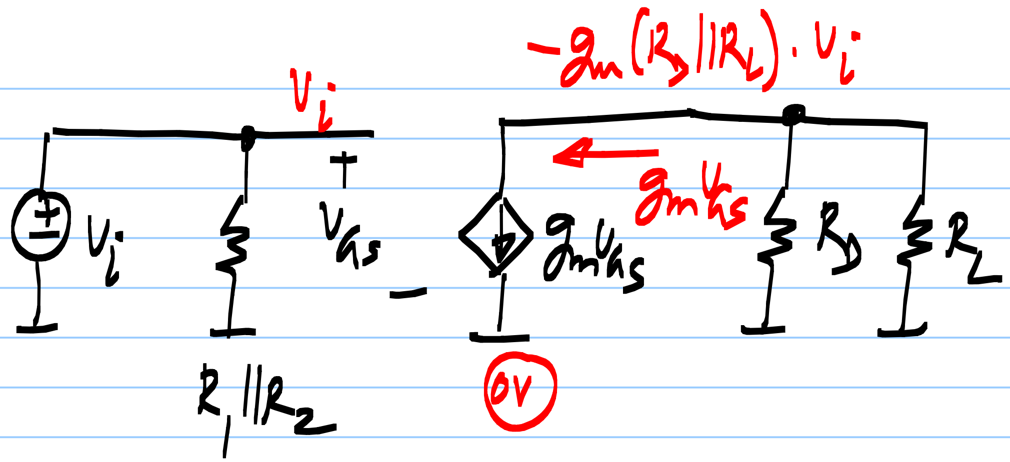
op. point		incremental quantities
$V_{GS0} = 3V$	+	$v_{gs} = v_i$
$V_{DS0} = 4V$	+	$v_{ds} = -g_m(R_D \| R_L)v_i = -5v_i$
$I_{D0} = 200\mu A$	+	$i_d = g_m v_i = 200\mu S \cdot v_i$

$$-1V \le v_i \le 1/3\,V \checkmark$$

$$\frac{R_2}{R_1+R_2} = \frac{4}{15}$$

$$v_i = V_p \cos(\omega t)$$

$$V_p < 1/3\,V$$



$-g_m(R_D \| R_L) \cdot v_i$
v_i
$+$
v_{GS}
$-$
v_i
$g_m v_{GS}$
$g_m v_{GS}$
R_D
R_L
$R_1 \| R_2$
0V

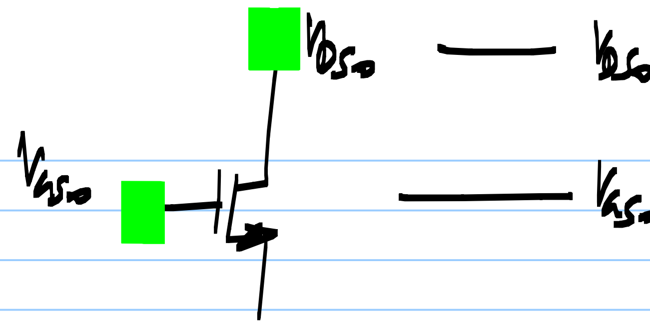
Total quantities:

$$V_{GS,tot} = V_{GS0} + v_i = 3V + v_i$$

$$V_{DS,tot} = V_{DS0} - g_m (R_D \| R_L) v_i = 4V - 5v_i$$

$$I_{D,tot} = I_{D0} + g_m v_i = 200\mu A + 200\mu S \cdot v_i$$

Limit imposed by the triode region:



In saturation if $V_{DS,tot} \geq V_{GS,tot} - V_T$

$$V_{DSo} - g_m (R_D \| R_L)\, v_i \geq V_{GSo} + v_i - V_T$$

$$v_i \leq \frac{V_{DSo} - V_{GSo} + V_T}{1 + g_m (R_D \| R_L)}$$

(Ensures that the transistor is in saturation)

Cutoff limit :

To avoid cutoff, $I_{D,tot} > 0$

$$I_{D_0} + g_m v_i > 0$$

$$v_i > -\frac{I_{D_0}}{g_m} \; ; \; v_i > -\frac{(V_{GS_0} - V_T)}{2}$$

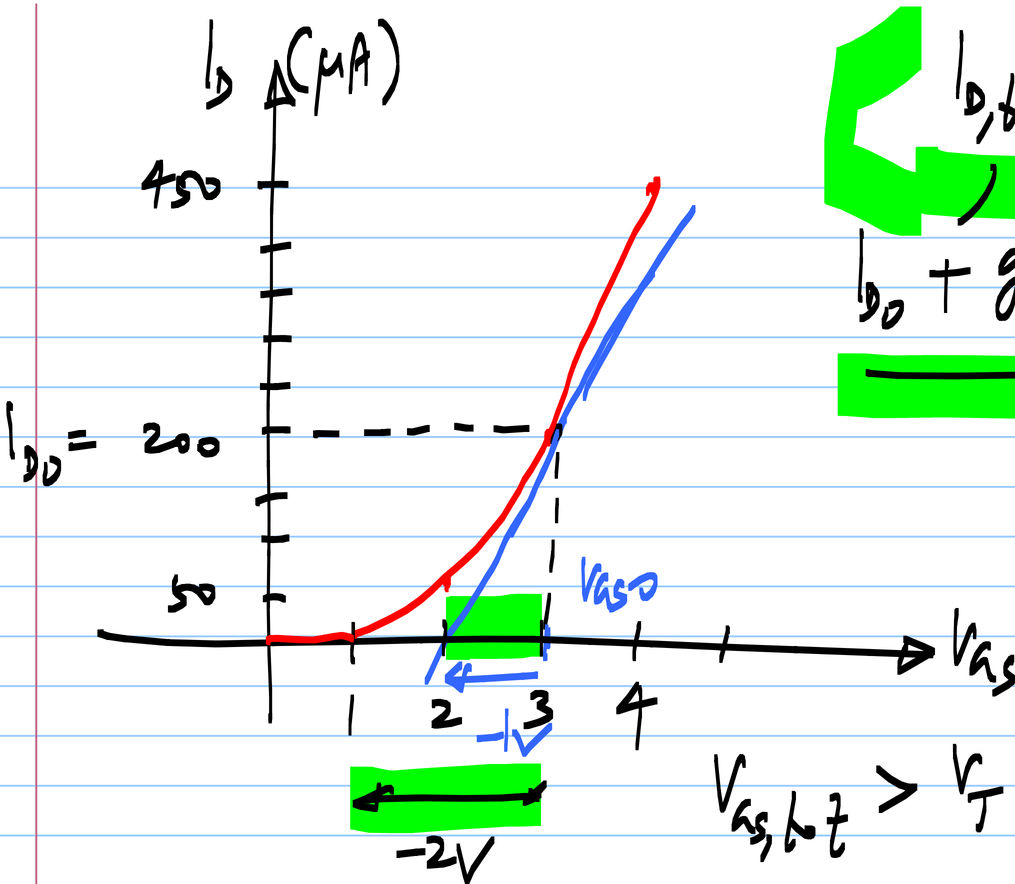
$$g_m = \frac{2 \cdot I_{D_0}}{(V_{GS_0} - V_T)}$$

Cutoff limit: $v_{GS} < V_T$

To avoid cutoff, $v_{GS,tot} > V_T$

$$V_{GS_0} + v_i > V_T$$

$$\boxed{v_i > -(V_{GS_0} - V_T)}$$



$V_{GS,tot} > V_T$

$I_{D,tot} > 0$

$I_{D0} + g_m v_i$

Triode region limit

in sat. region if $v_i \le \dfrac{V_{DS_0} - V_{GS_0} + V_T}{1 + g_m(R_D \| R_L)} = \dfrac{4V - 3V + 1V}{1+5}$

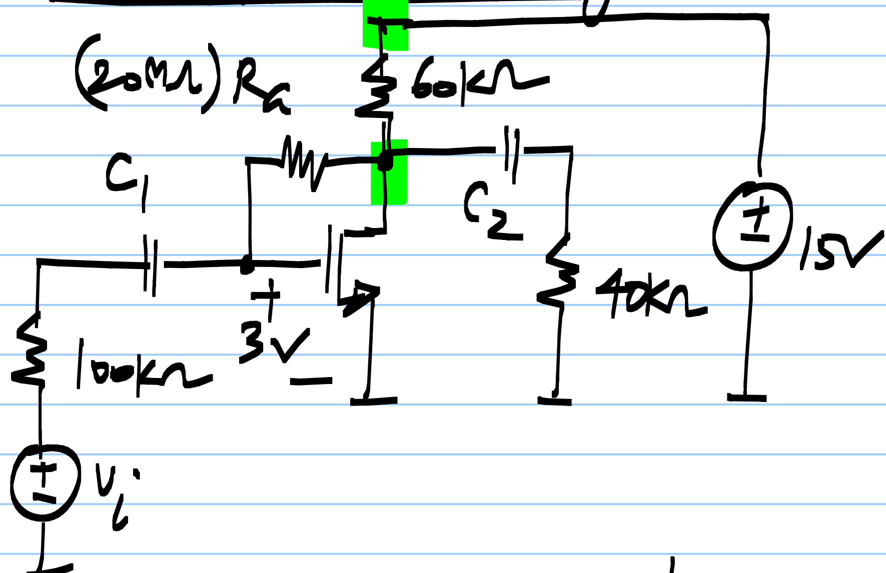
$v_i \le \dfrac{2}{6} = \dfrac{1}{3} V$

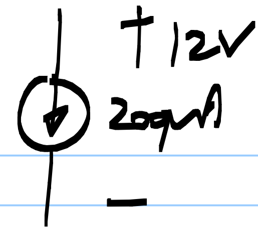
Cutoff limit : $v_i \ge -\dfrac{I_{D0}}{g_m} = -\dfrac{200\mu A}{200\mu S} = -1V$

$v_i \ge -(V_{GS_0} - V_T) = -2V$

$3V \quad 1V$

CS amplifier using drain feedback





$\equiv$ $\frac{12V}{0.2mA} = 60k\Omega$

C_1, C_2, R_G : very large

Total $V_{GS}, V_{DS}, \underline{\underline{I_D}}$ = op. point + $\underbrace{\text{increment}}$

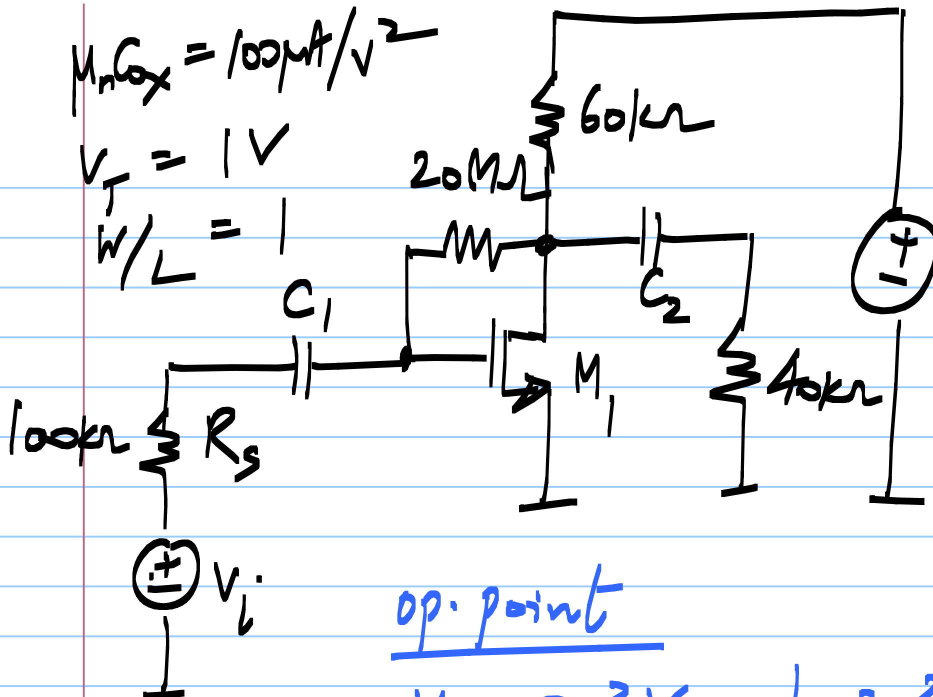
$V_{DS,TOT} \geq V_{GS,TOT} - V_T$

$V_{D,TOT} \geq V_{G,TOT} - V_T$

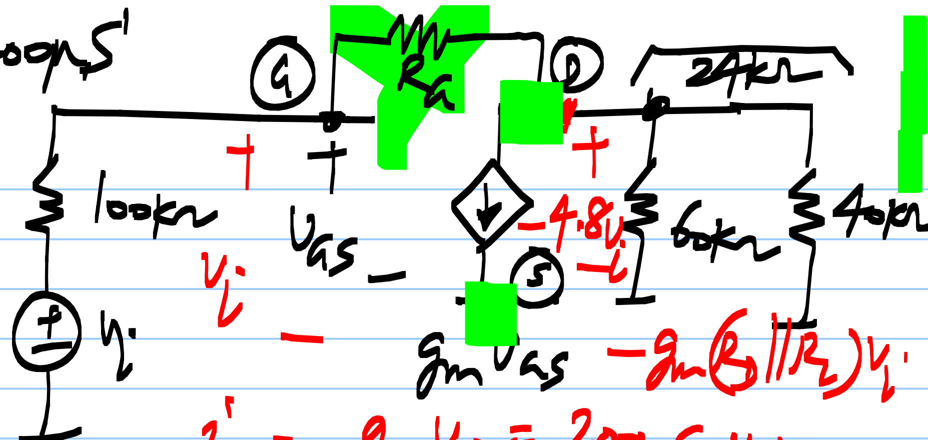
$\mu_n C_{ox} = 100\,\mu A/V^2$

$V_T = 1\,V$

$W/L = 1$



$g_m = 200\,\mu S$



$i_D' = g_m v_i = 200\,\mu S \cdot v_i$

op. point

$V_{GS_0} = 3V$, $I_{D_0} = 200\,\mu A$

$V_{DS_0} = 3V$

increment

$v_{GS} = v_i$, $i_D' = 200\,\mu S \cdot v_i$

$v_{DS} = -4.8 v_i$

Total:

$V_{GS,tot} = 3V + v_i$

$V_{DS,tot} = 3V - 4.8\,v_i$

$i_{D,tot} = 200\mu A + 200\mu S \cdot v_i$

To prevent M_1 from going into triode region,

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

$V_{DS_0} - g_m(R_D \| R_L)\, v_i > V_{GS_0} + v_i - V_T$

$$v_i < \frac{V_{DS_0} - V_{GS_0} + V_T}{1 + g_m(R_D \| R_L)}$$

$$v_i < \frac{1V}{5.8} = \underline{0.17V}$$

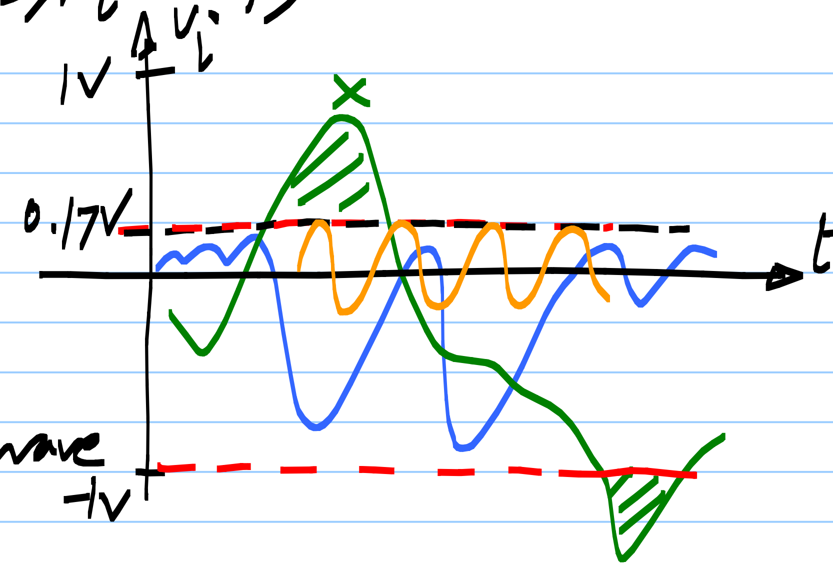
To prevent cut-off of M_1 $(v_{GS,tot} > V_T)$

$\underline{i_{D,tot} > 0}$ $\qquad I_{D0} + g_m v_i > 0$

$v_i > -\dfrac{I_{D0}}{g_m} = \dfrac{-200\mu A}{200\mu S} = \underline{-1V}$

$\underbrace{-1V < v_i}_{\text{cut-off}} \le \underbrace{0.17V}_{\text{Triode}}$

Max, sinewave amplitude $= \underline{0.17V}$



$v_o = -4.8 v_i$

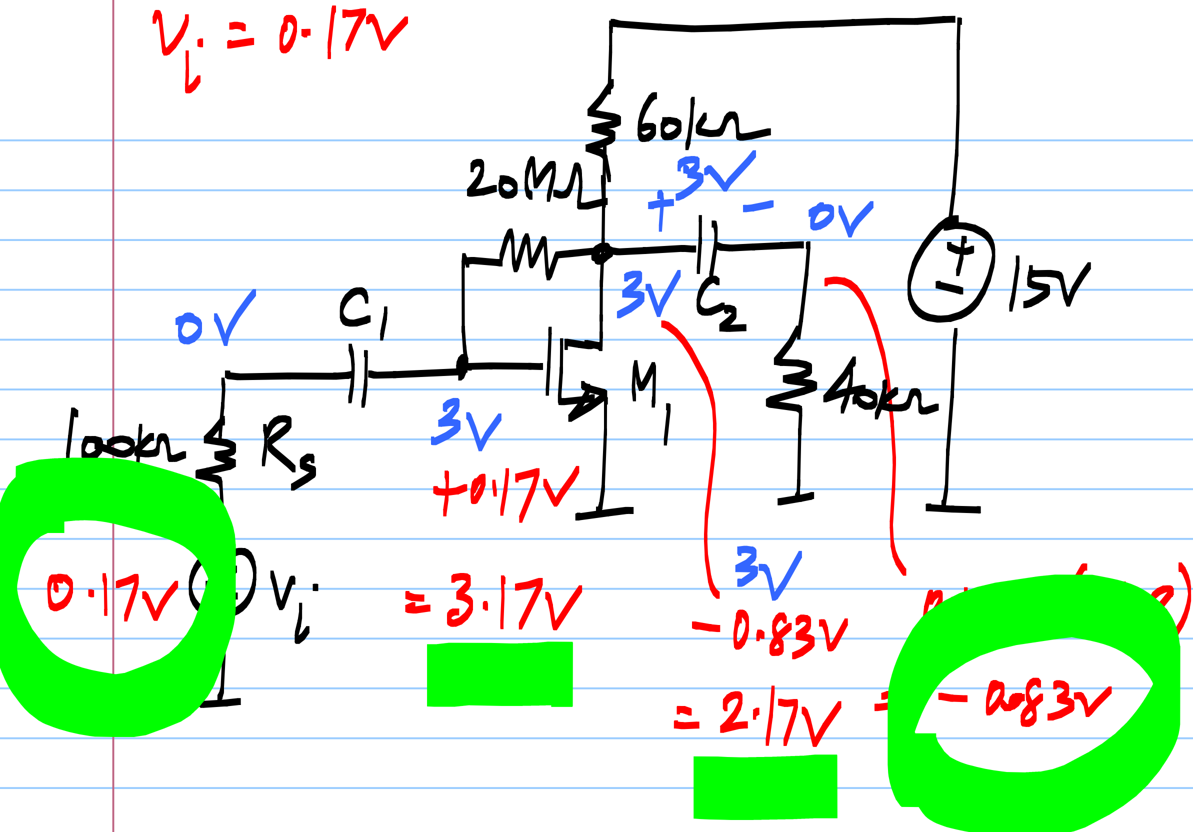
$-1V \le v_i \le 0.17V$

cutoff

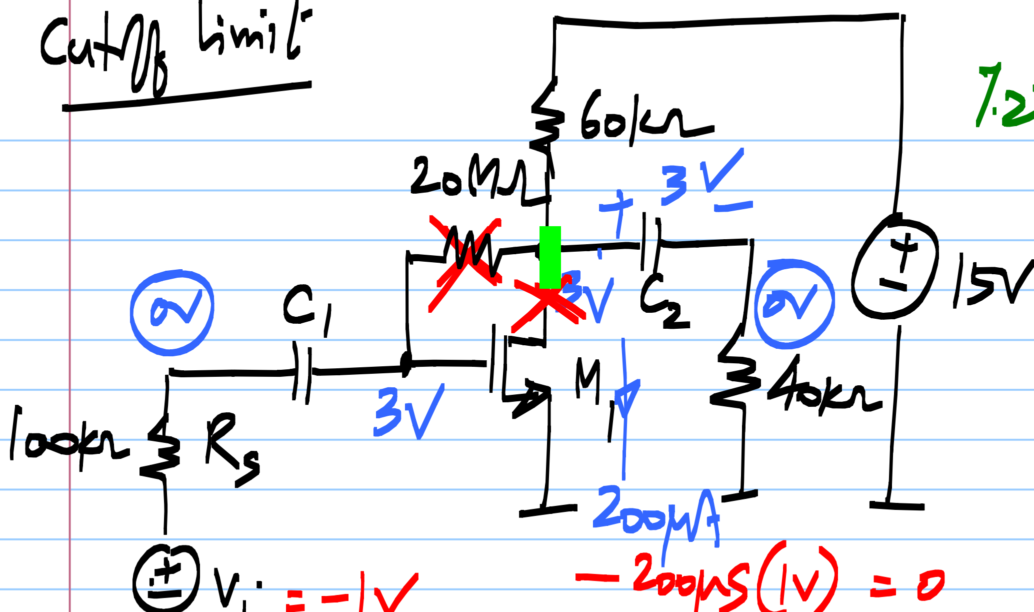
triode

$-0.83V \le v_o \le 4.8V$

$v_i = 0.17V$


60kΩ
20MΩ
3V
+ −
0V
15V
C1
C2
3V
0V
M1
40kΩ
100kΩ
Rs
3V
+0.17V
= 3.17V
0.17V
vi
3V
−0.83V
= 2.17V
− 0.83V

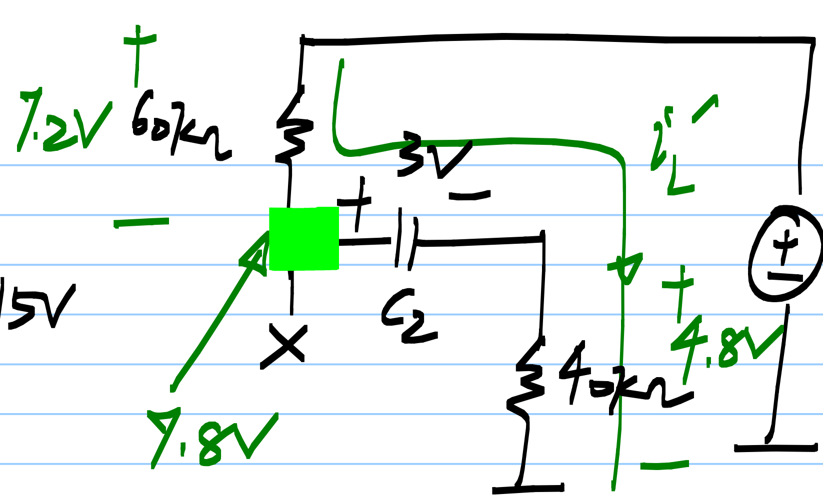
Cutoff limit:



$-200\mu S(1V) = 0$

$V_{gs} = -1V$

$g_m V_{gs} = 200\mu S(-1V)$



$i_L' = \frac{15V - 3V}{100k\Omega} = 120\mu A$

$3V + 4.8V = 7.8V$

Swing limit calculation

Summary.

* Evaluate $V_{GS,tot}$, $V_{DS,tot}$ & $i_{D,tot}$

* $tot = op.point + \underbrace{incremental}_{\text{s.s ckt} \quad \text{linear eq.}}$

* Apply triode & cutoff limits in terms of v_i or v_o

Circuits with multiple transistors

* Calculate triode/cutoff limit for one transistor at a time

M_1 $-1.5V \leq v_i \leq 0.5V$

M_2 $-0.75V \leq v_i \leq 1V$

$-0.75V \leq v_i \leq 0.5V$