Amplifiers, Source followers & Cascodes

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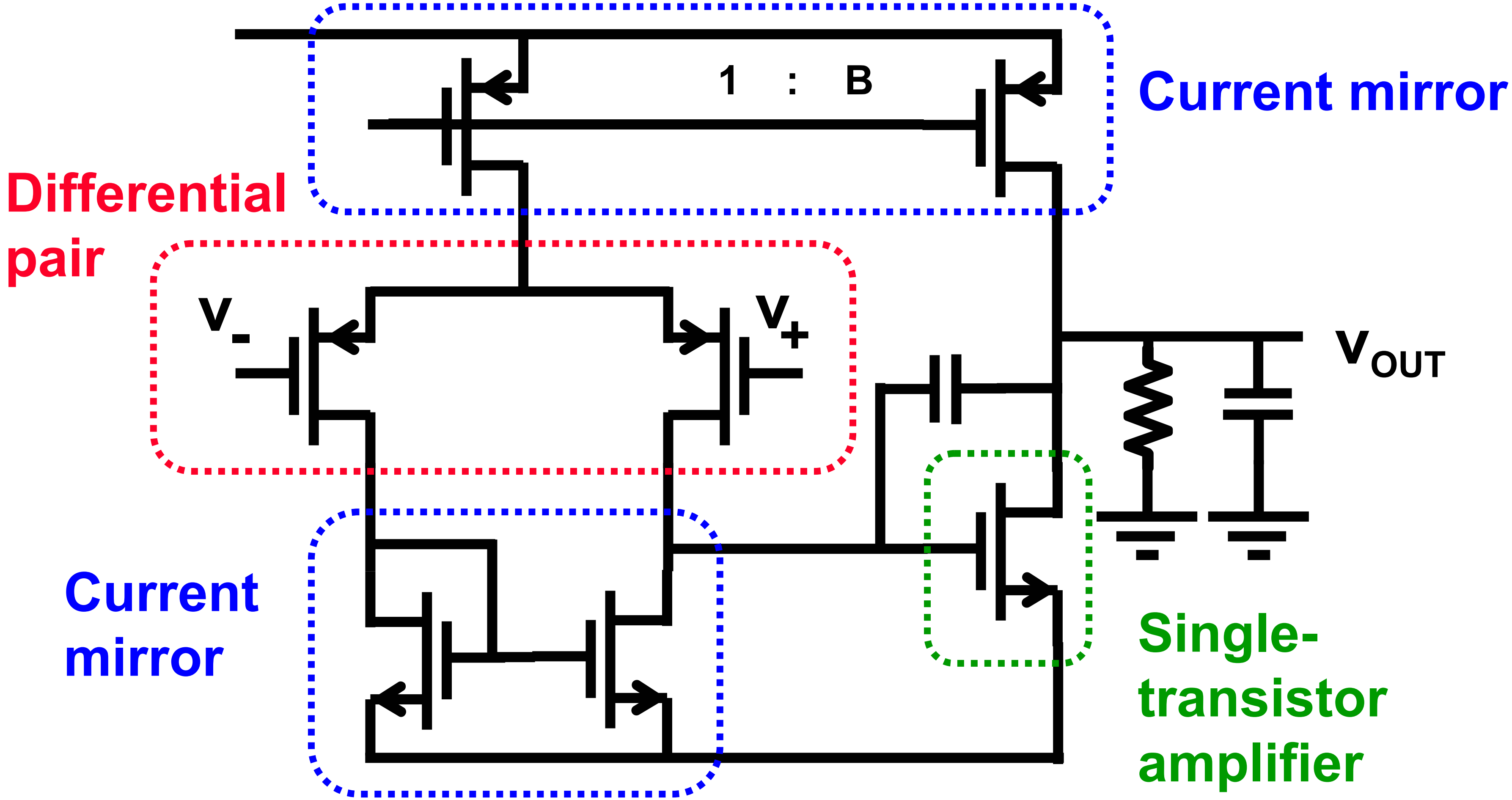
Operational amplifier



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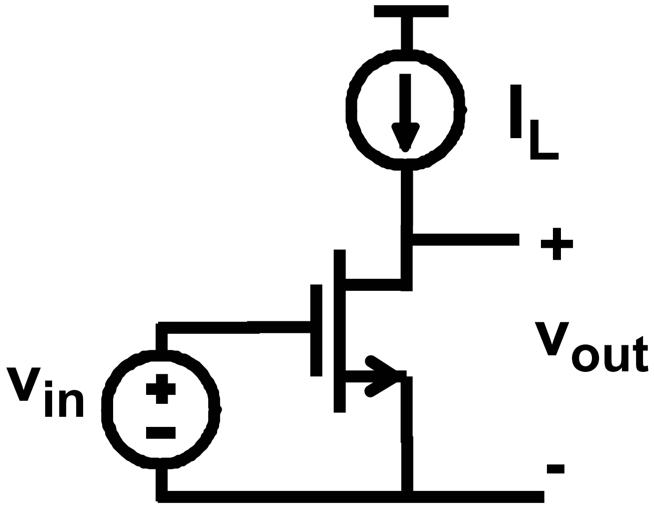
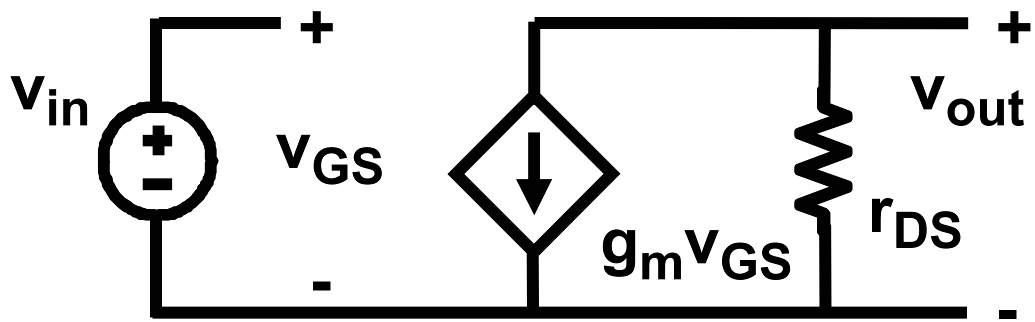
Single-transistor amplifier - 1





$$A_v = g_m r_{DS} = \frac{2\,I_{DS}}{V_{GS}-V_T}\,\frac{V_E\,L}{I_{DS}} = \frac{2\,V_E\,L}{V_{GS}-V_T}$$

$A_v \approx 100$ if $V_E L \approx 10$ V and $V_{GS}-V_T \approx 0.2$ V

Single-transistor amplifier - 2

High gain ?

Low V_{GS}-V_T and large L !!!

MOST or bipolar amplifier ?

MOST $$A_v = \frac{V_E L}{(V_{GS}-V_T)/2}$$

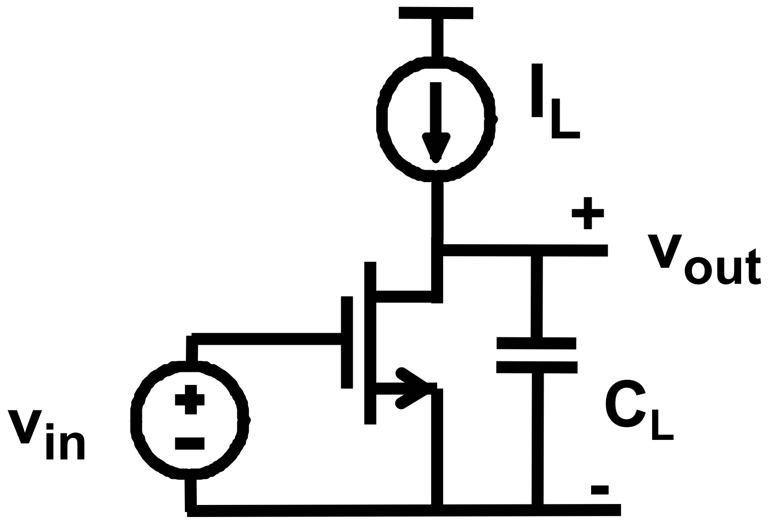
$A_v \approx 100$ if $V_E L \approx 10$ V and $V_{GS}-V_T \approx 0.2$ V

Bipolar $$A_v = \frac{V_E}{kT/q}$$

$A_v \approx 1000$ if $V_E \approx 26$ V since $kT/q = 26$ mV

3 vs 2 stages for 10^6

Gain, Bandwidth and Gain-bandwidth



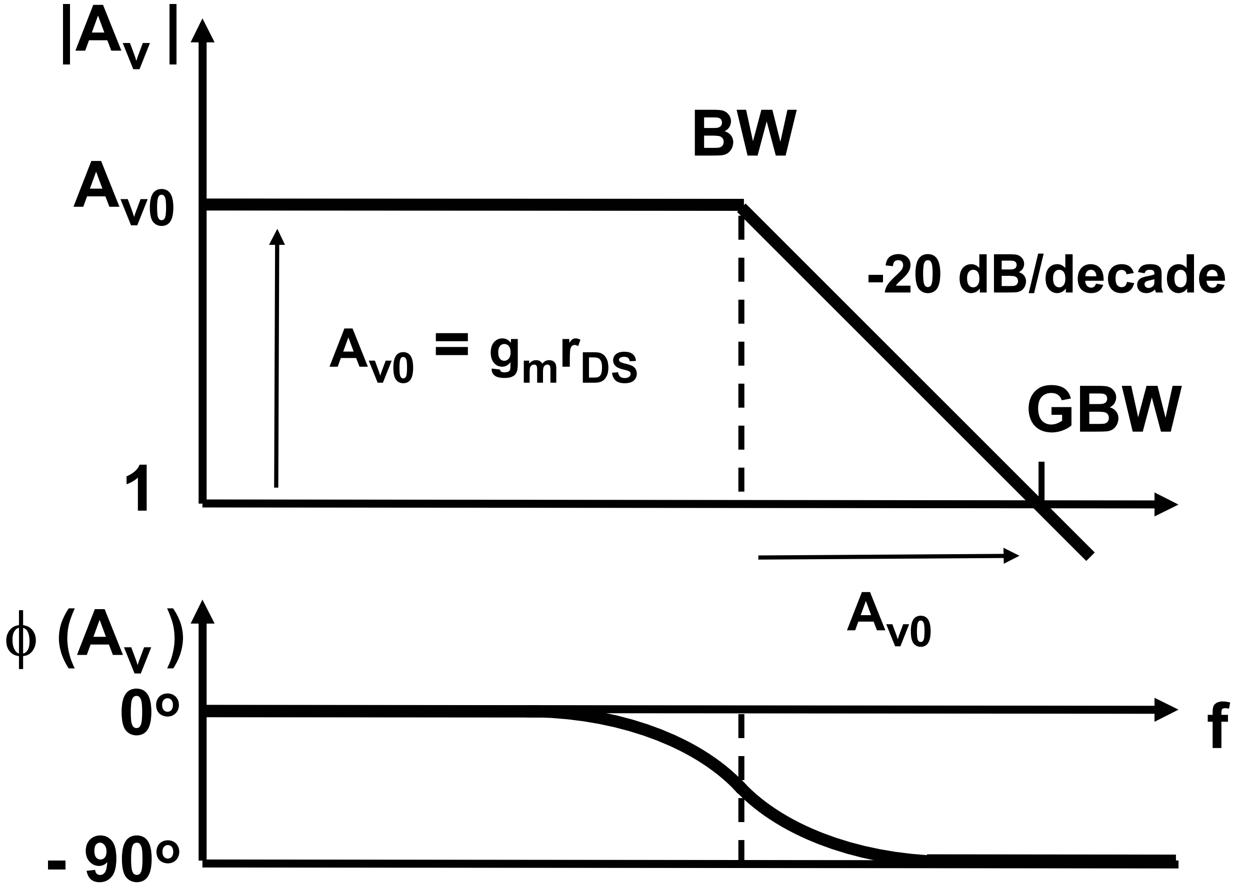
$$A_{v0} = g_m r_{DS}$$

$$BW = \frac{1}{2\pi\, r_{DS} C_L}$$

$$GBW = \frac{g_m}{2\pi\, C_L}$$

For all single-stage Operational amplifiers

Gain A_v , BW and GBW



$$GBW = \frac{g_m}{2\pi\, C_L}$$

$\phi\,(A_v) = -\,45^o$ at BW

Single-transistor amplifier : Exercise

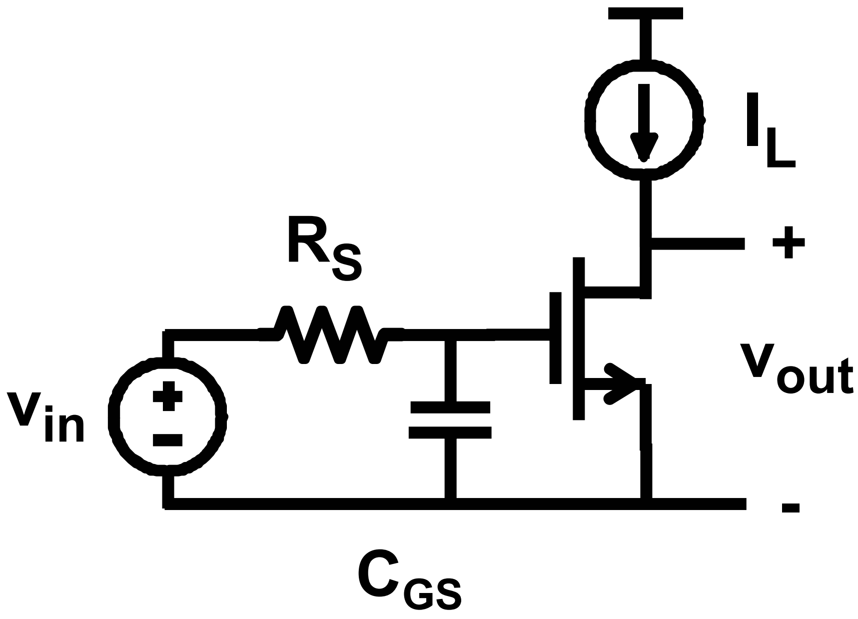
GBW = 100 MHz for C_L = 3 pF

Techno.: $K'_n \approx 50\ \mu A/V^2$
$L_{min} = 0.5\ \mu m$

I_{DS} ? L ? W ?

$\frac{GBW.C_L}{I_{DS}}$?

Gain, Bandwidth and Gain-bandwidth



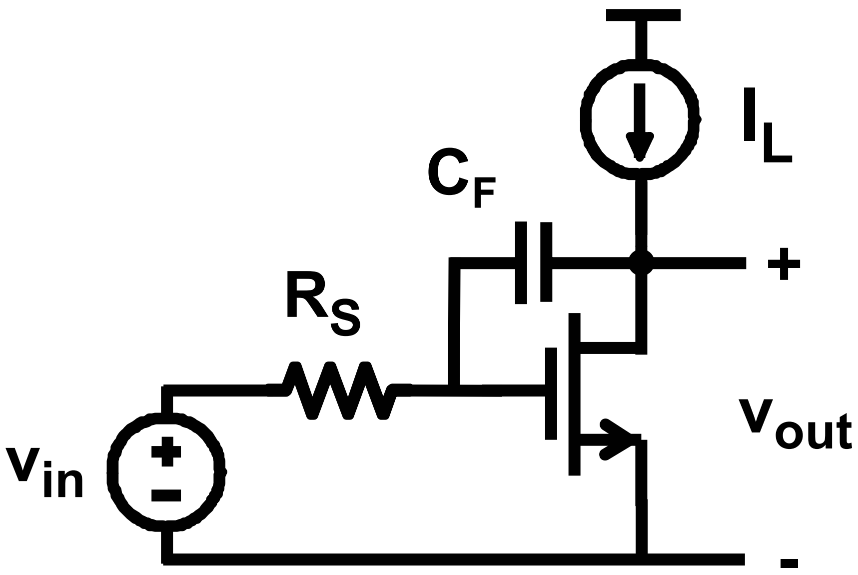
$$A_{v0} = g_m r_{DS}$$

$$BW = \frac{1}{2\pi\, R_S C_{GS}}$$

$$GBW = \frac{g_m}{2\pi\, C_{GS}} \frac{r_{DS}}{R_S} = f_T \frac{r_{DS}}{R_S} \sim \frac{1}{WC_{ox}} \frac{1}{V_{GS}-V_T}$$

W ? L ? V_{GS}-V_T?

Gain, Bandwidth and Gain-bandwidth

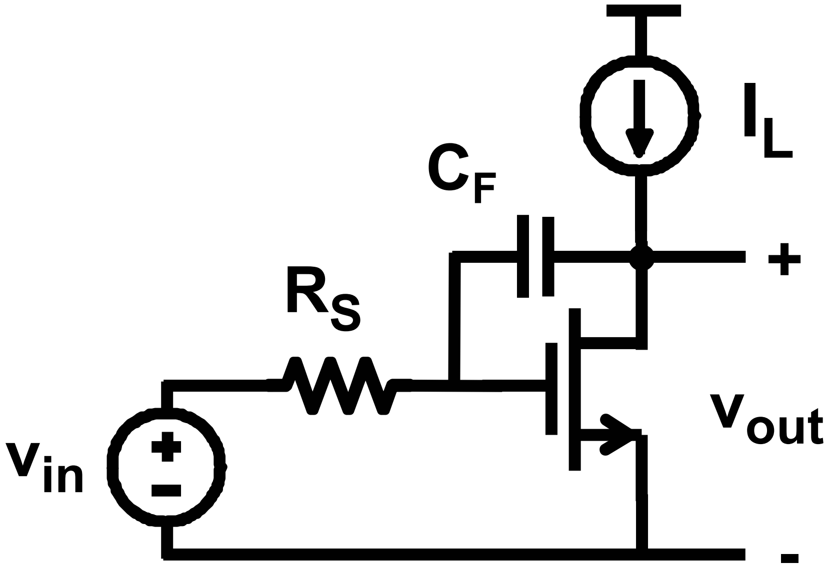


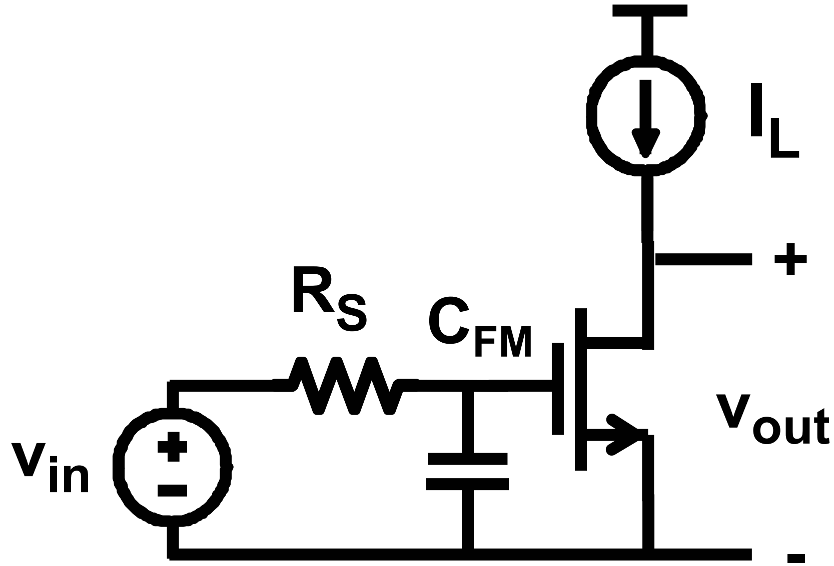
$$A_{v0} = g_m r_{DS}$$

$$BW = \frac{1}{2\pi\, R_S\, A_{v0}\, C_F}$$

$$GBW = \frac{1}{2\pi\, R_S\, C_F}$$

Miller effect



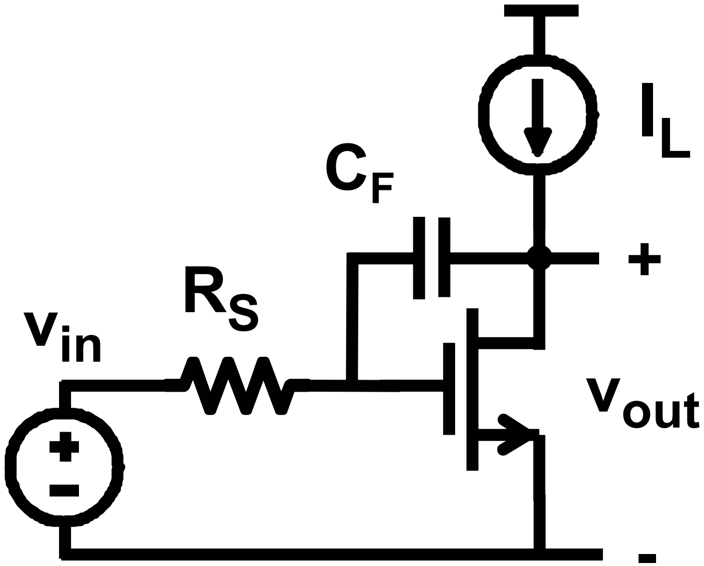


$A_{v0} = g_m r_{DS}$

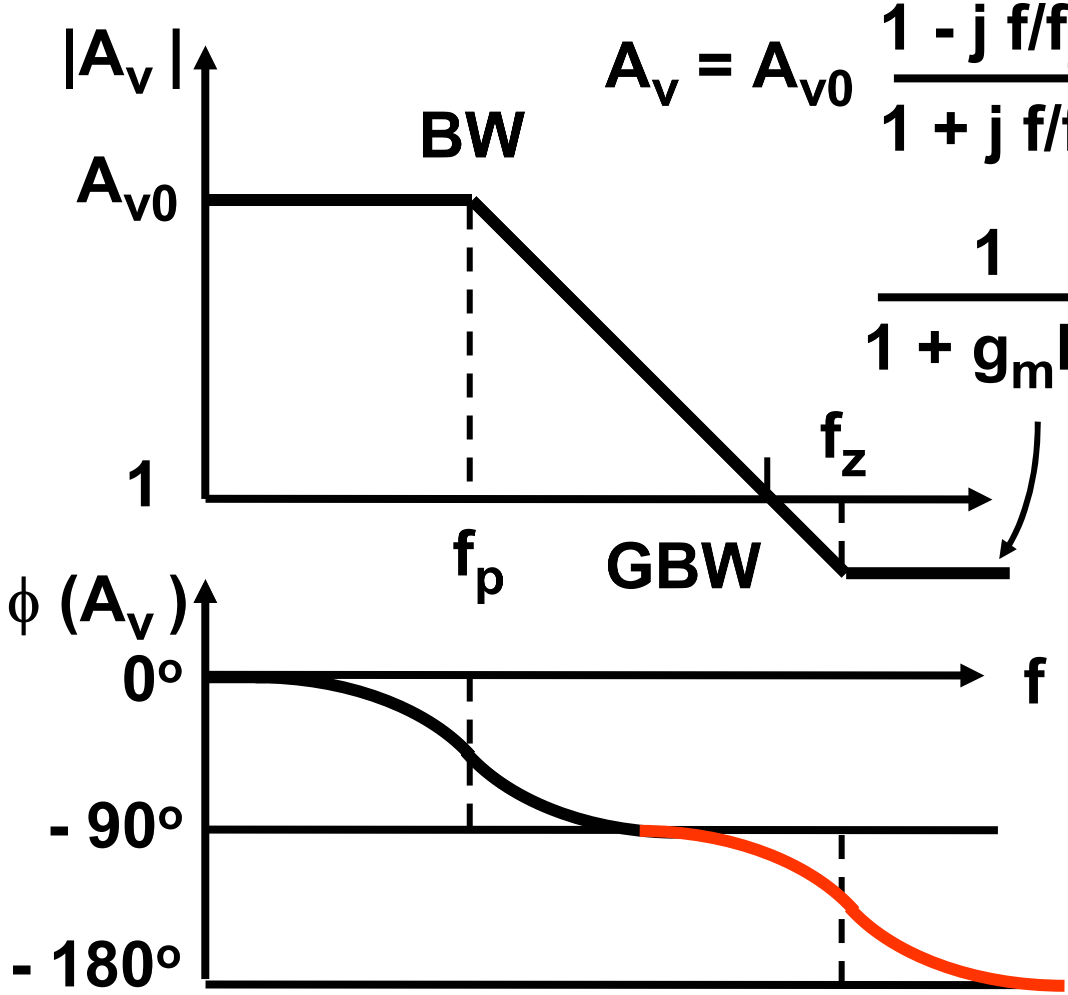
$C_{FM} = (1+A_{v0})\ C_F$

Miller, Dependence of the input impedance of a three-electrode vacuum tube upon the load in the plate circuit, Scient. Papers Bur. Standards, 1920, 367-385.

Miller capacitance feedback effects



$$f_z = \frac{g_m}{2\pi C_F}$$

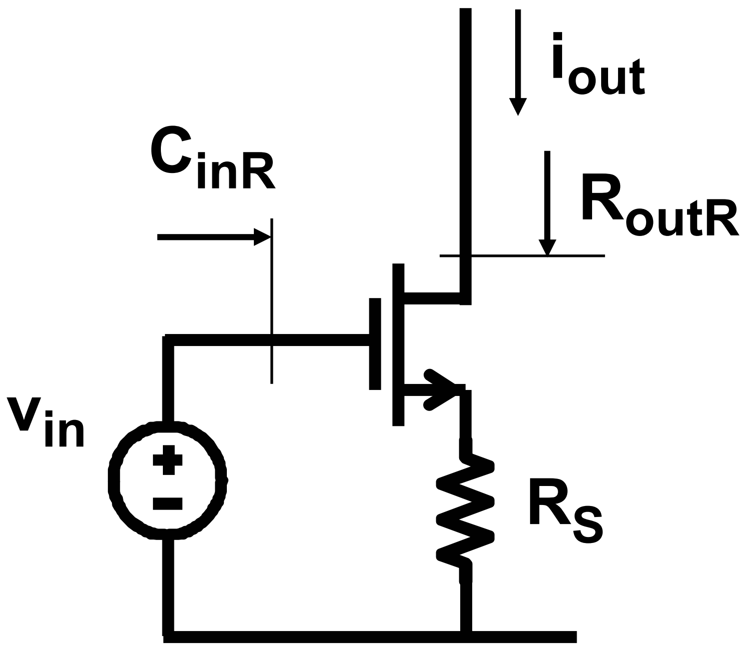


$$A_v = A_{v0}\frac{1 - j\, f/f_z}{1 + j\, f/f_p}$$

$$\frac{1}{1 + g_m R_S}$$

For phase, a positive zero is like a negative pole !!!

Amplifier with local R- (series) feedback



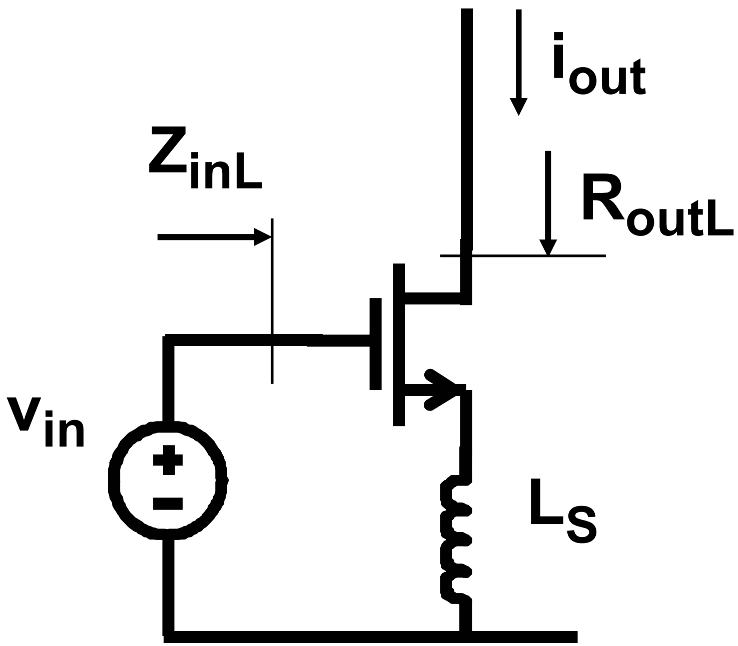
$$g_{mR} = \frac{g_m}{1 + g_m R_S} \sim \frac{1}{R_S}$$

$$R_{outR} = r_{DS}\,(1 + g_m R_S)$$
$$\approx (g_m r_{DS})\, R_S$$

$$C_{inR} = \frac{C_{GS}}{1 + g_m R_S}$$

But R_S gives extra noise !

Amplifier with local L- feedback



$$g_{mL} = \frac{g_m}{1 + g_m L_S s}$$

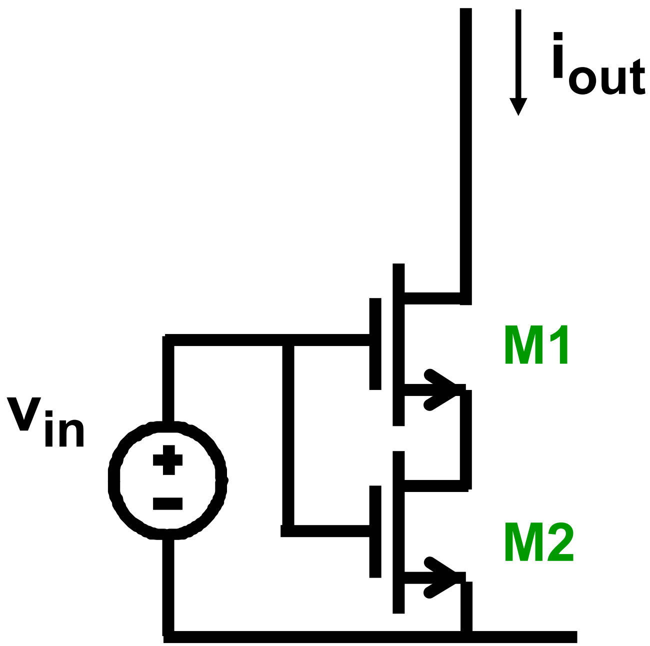
$$R_{outL} = r_{DS}\,(1 + g_m L_S s)$$

$$Z_{inL} = g_m \frac{L_S}{C_{GS}} + \frac{1 + L_S C_{GS}\, s^2}{s\, C_{GS}}$$

No extra noise !

$$Z_{inL} = L_S\,\omega_T + L_S s + \frac{1}{s\, C_{GS}}$$

Amplifier with local MOST-R- Feedback



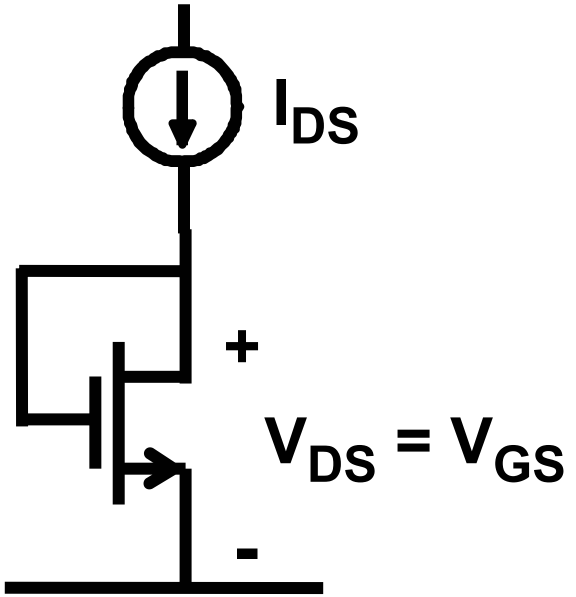
$$V_{DS2} = V_{GS2} - V_{GS1} \approx 0.2\ V$$

$$r_{DS2} = \frac{1}{KP\ W_2/L_2\ (V_{GS2}-V_T)}$$

$$R_{outR} = r_{DS1}\ (1 + g_{m1}\ r_{DS2})$$

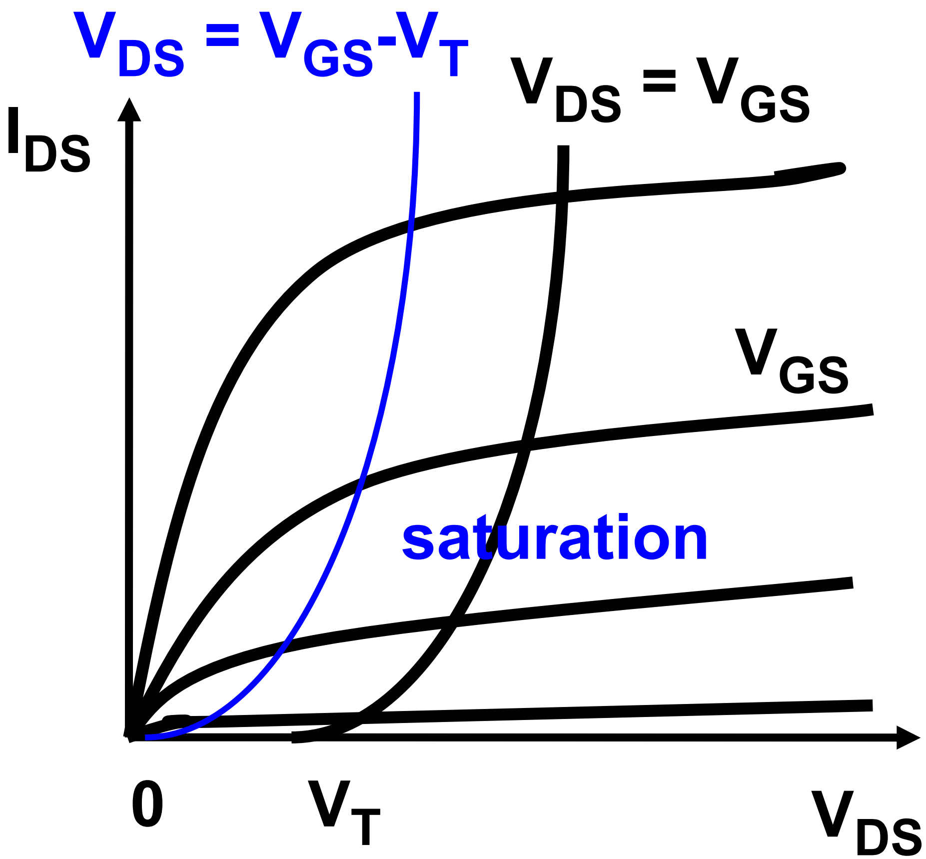
$$C_{inR} = \frac{C_{GS1}+C_{GS2}}{1 + g_{m1} r_{DS2}}$$

Diode-connected MOST : parallel Feedback

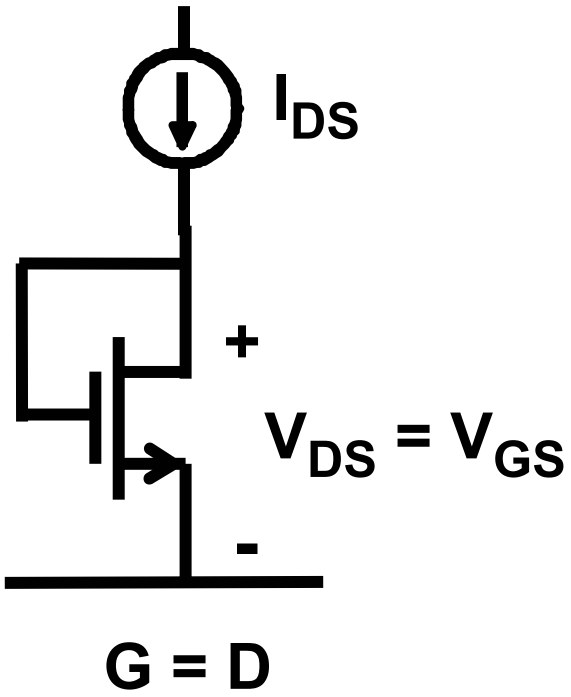


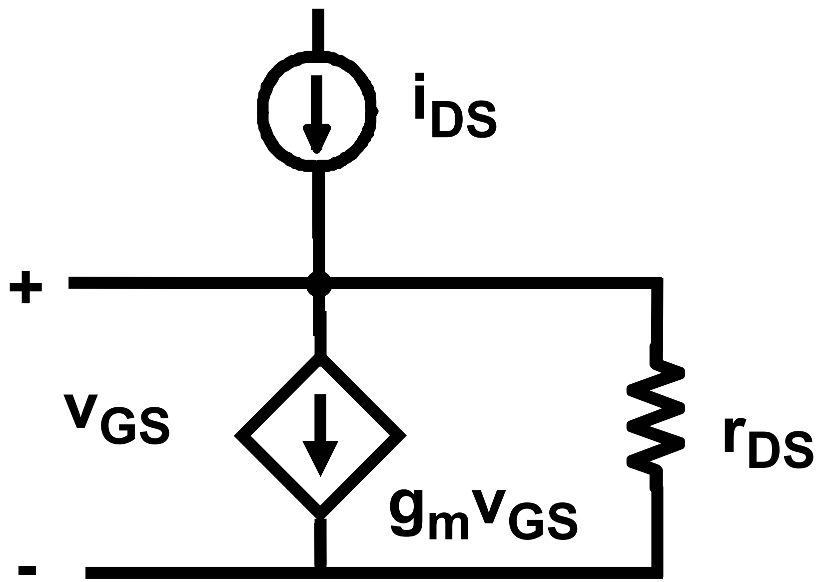
G = D

$$I_{DS} = K'_n \frac{W}{L} (V_{DS}-V_T)^2$$



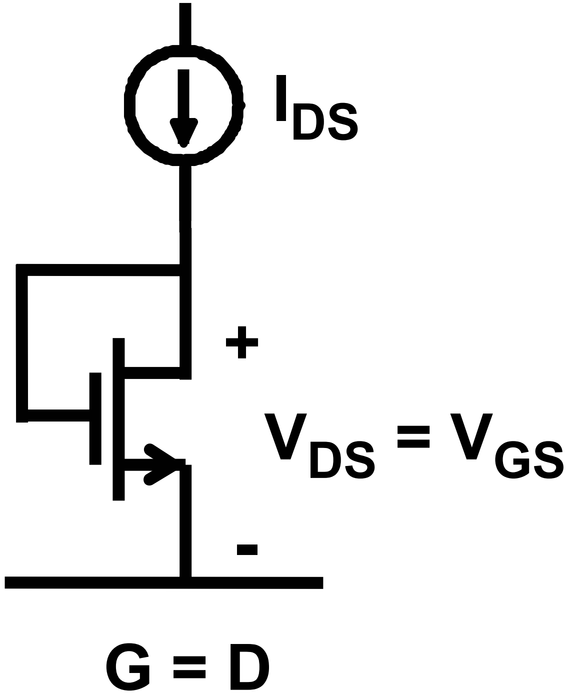
Diode-connected MOST: small-signal

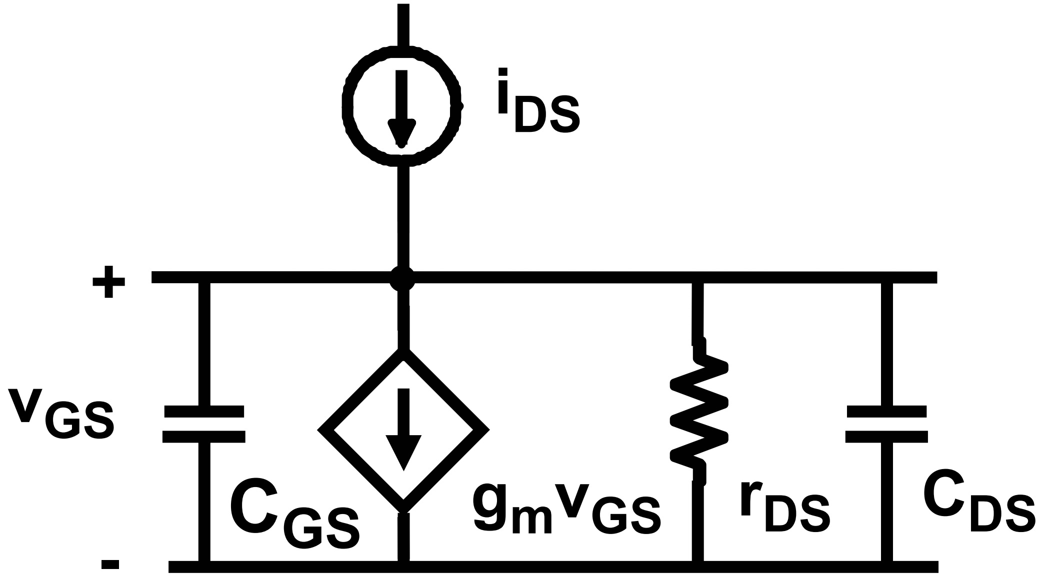




$$r_{ds} = 1/g_m \;//\; r_{DS} \approx 1/g_m$$

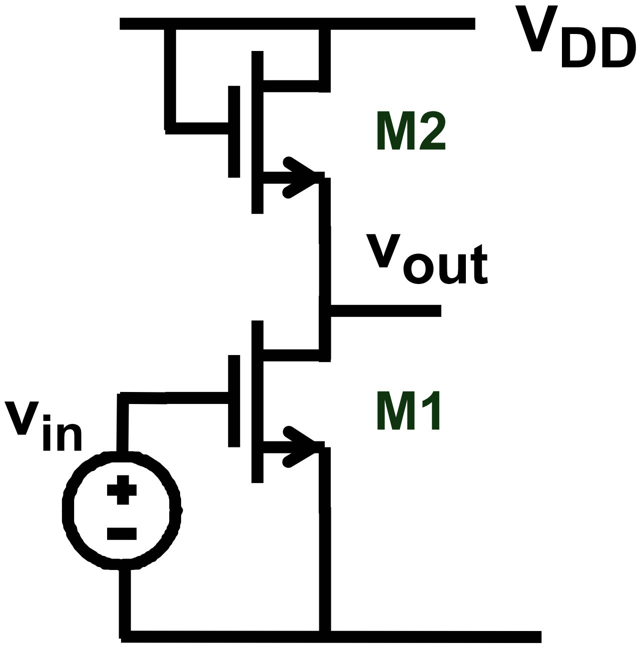
Diode-connected MOST at high frequencies





$$BW = \frac{g_m}{2\pi\,(C_{GS}+C_{DS})} \approx \frac{f_T}{2}$$

Wideband amplifier

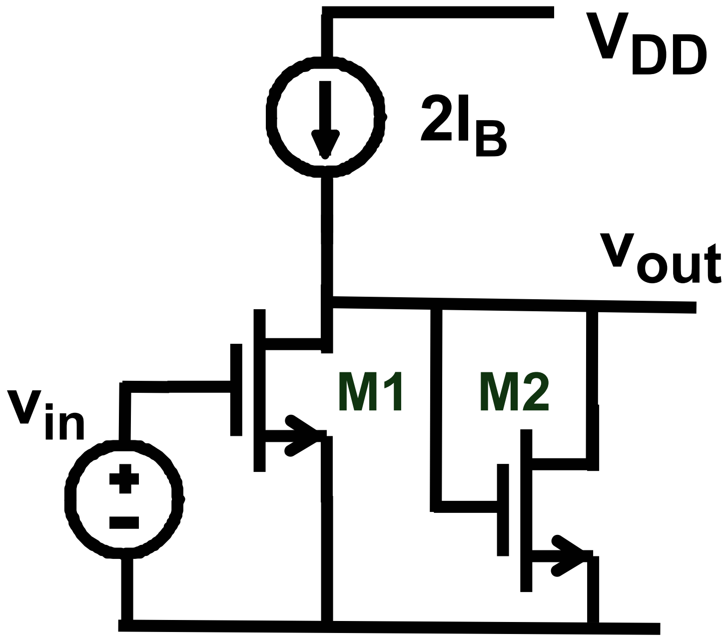


$$V_{OUT} = V_{DD} - V_{GS2}(V_{OUT})$$

$$A_{v0} = \frac{g_{m1}}{g_{m2}} = \sqrt{\frac{(W/L)_1}{(W/L)_2}} = \frac{V_{GS2} - V_T}{V_{GS1} - V_T}$$

$$R_{OUT} = 1/g_{m2}$$

Linear wideband amplifier



$V_{OUT} = V_{GS2}$

$$A_{v0} = \frac{g_{m1}}{g_{m2}} = \sqrt{\frac{(W/L)_1}{(W/L)_2}} = \frac{V_{GS2} - V_T}{V_{GS1} - V_T}$$

$R_{OUT} = 1/g_{m2}$

Current mirror with only nMOSTs

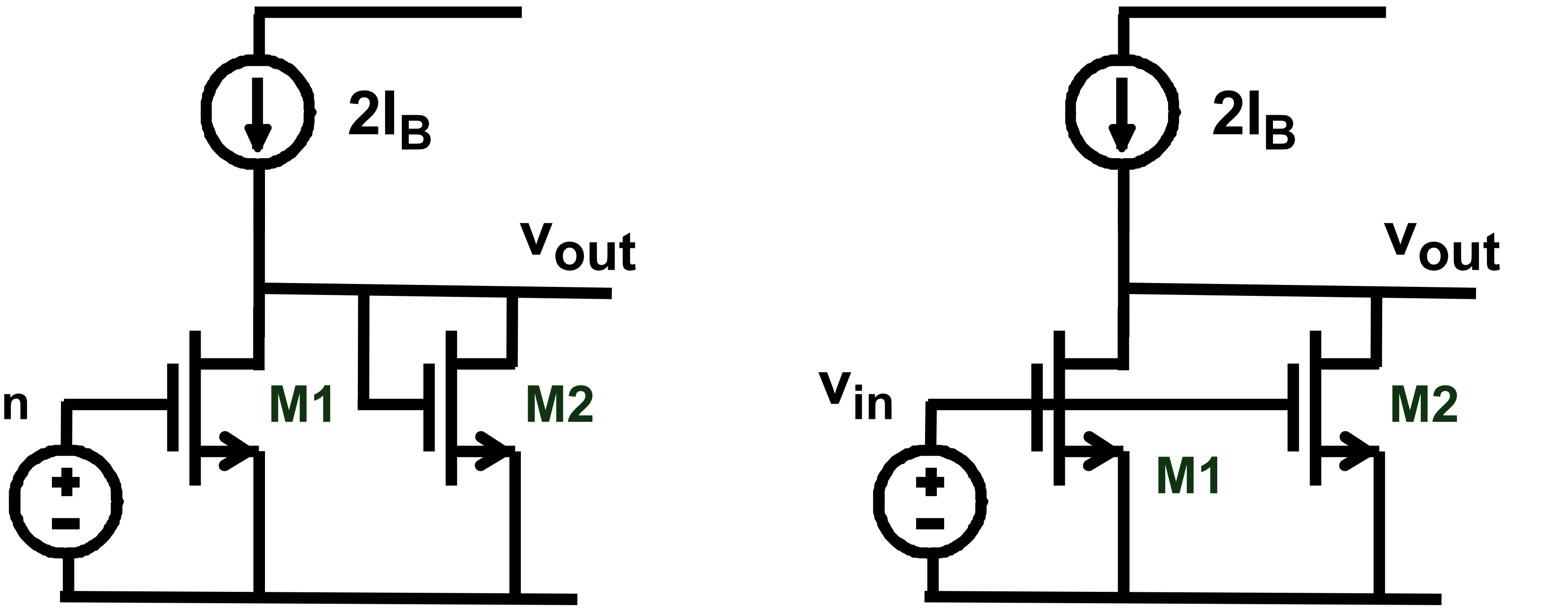
Same V_{OUTDC} as V_{INDC}

No body bias effect

Good PSRR

Double power consumption

Wideband amplifiers



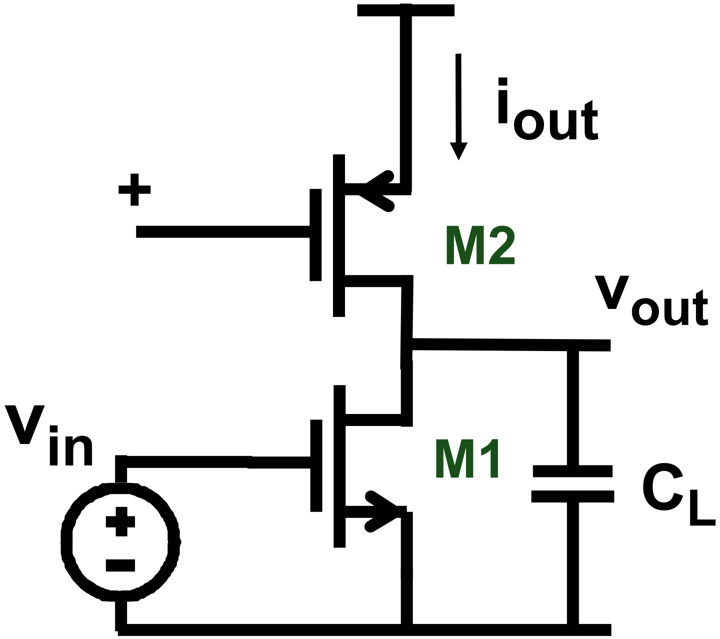
$$A_{v0} = \frac{g_{m1}}{g_{m2}} = \sqrt{\frac{(W/L)_1}{(W/L)_2}} = \frac{V_{GS2} - V_T}{V_{GS1} - V_T}$$

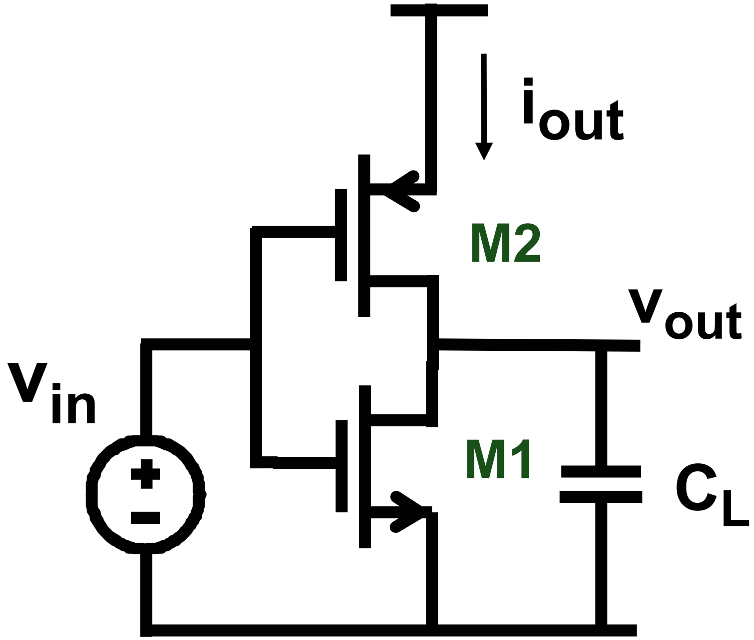
$$R_{out} = 1/g_{m2}$$

$$A_{v0} = g_m R_{out}$$

$$R_{out} = r_{DS1}//r_{DS2}$$

Class A versus class AB amplifier





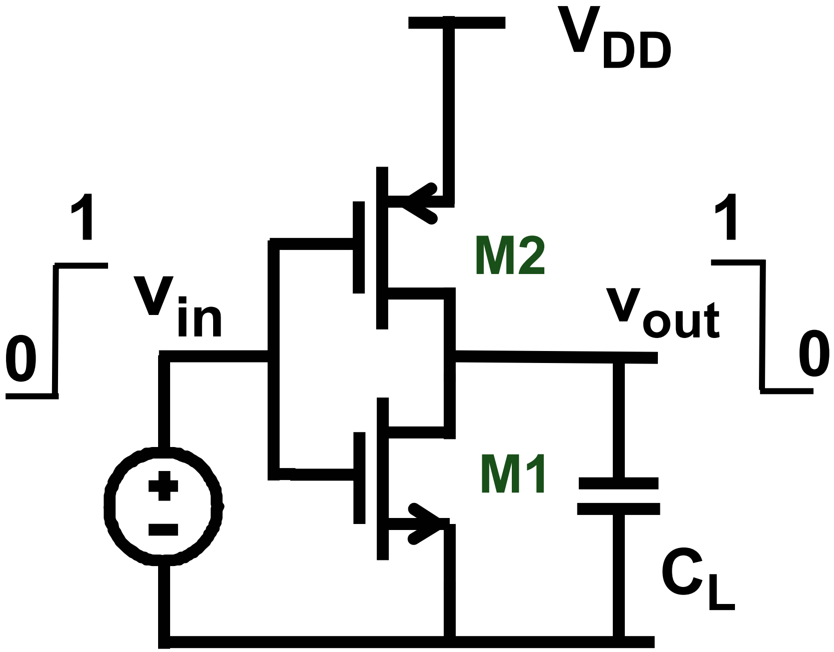
$$v_{out} = A_v\, v_{in}$$

Class A stage

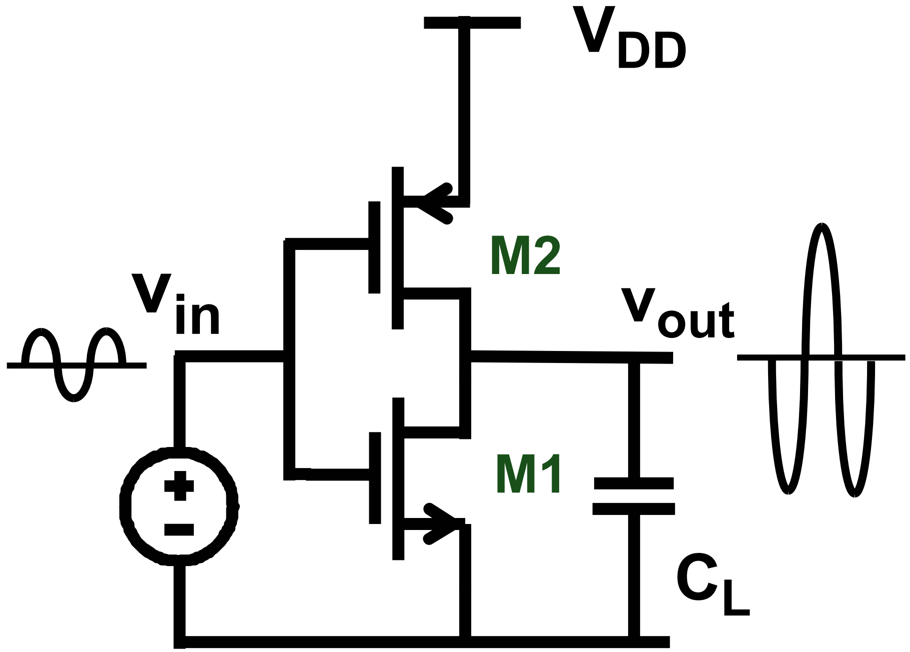
$$v_{out} = A_v\, v_{in}$$

Class AB stage

CMOS inverter-amplifier

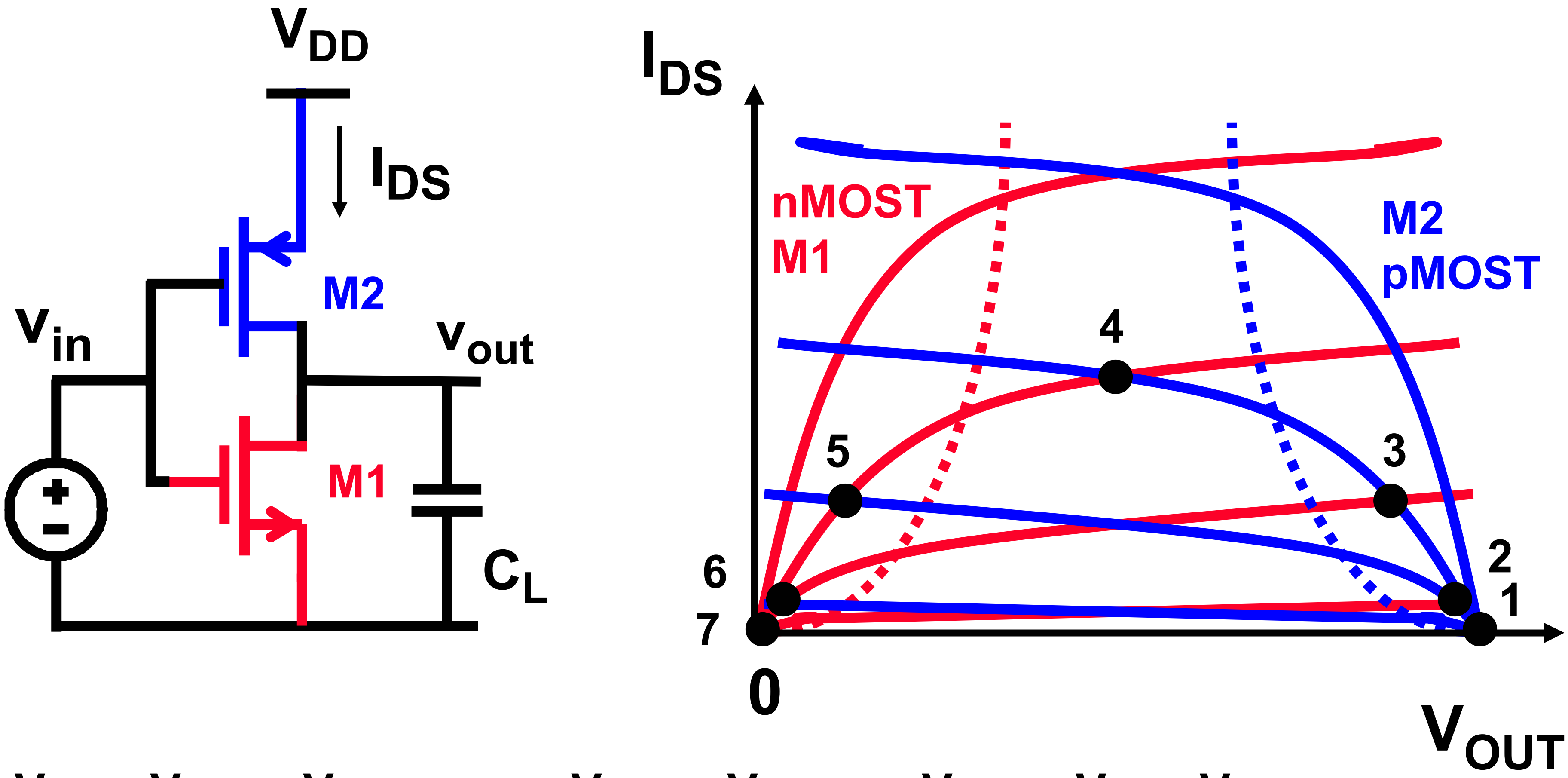


Digital invertor



Analog amplifier

Operating points nMOST & pMOST



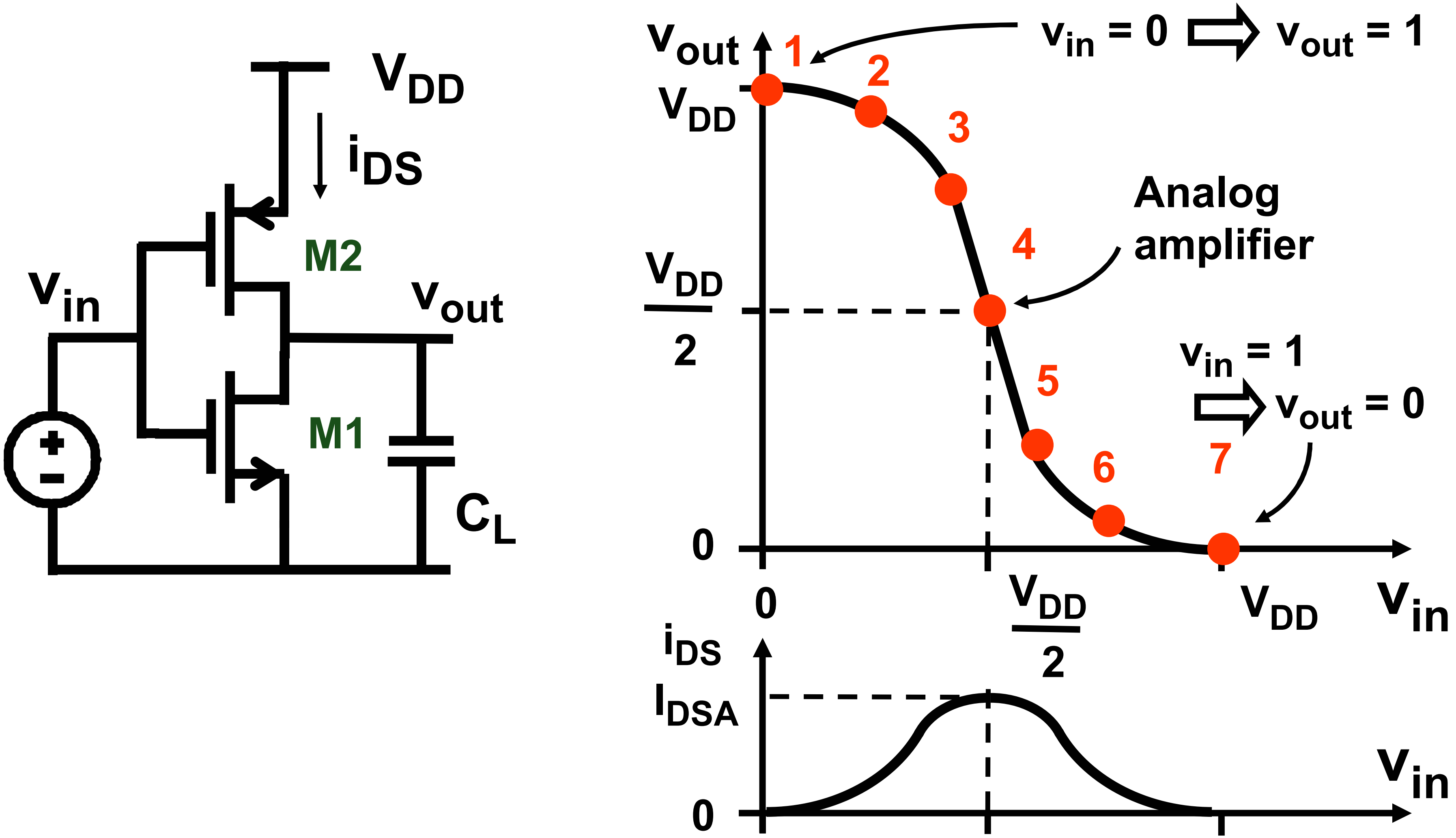
$V_{DD} = V_{DSn} + V_{DSp}$

$= V_{GSn} + V_{GSp}$

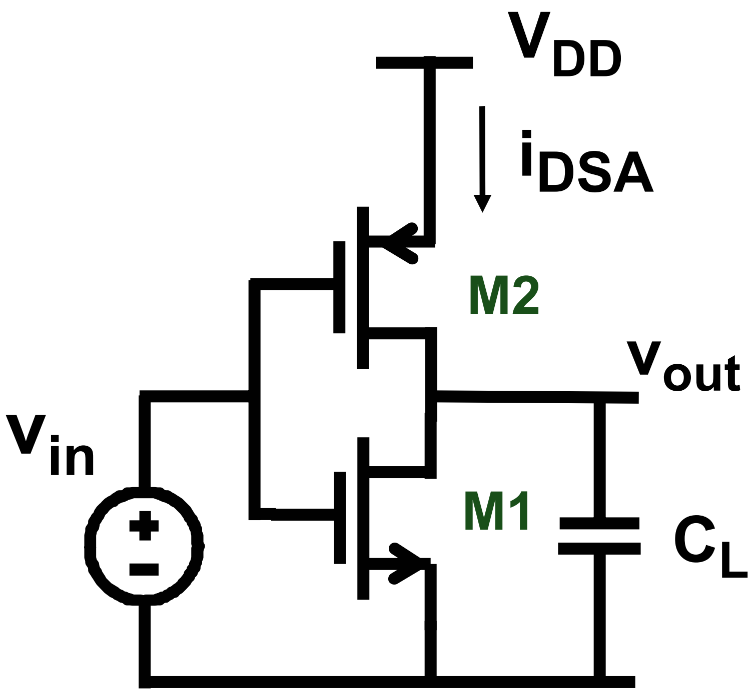
$V_{DSn} = V_{OUT}$ $\quad$ $V_{DSp} = V_{DD} - V_{OUT}$

$V_{GSn} = V_{IN}$ $\quad$ $V_{GSp} = V_{DD} - V_{IN}$

Transfer characteristic



Analog amplifier : DC



$$V_{in} = \frac{V_{DD}}{2} \Rightarrow V_{out} = \frac{V_{DD}}{2}$$

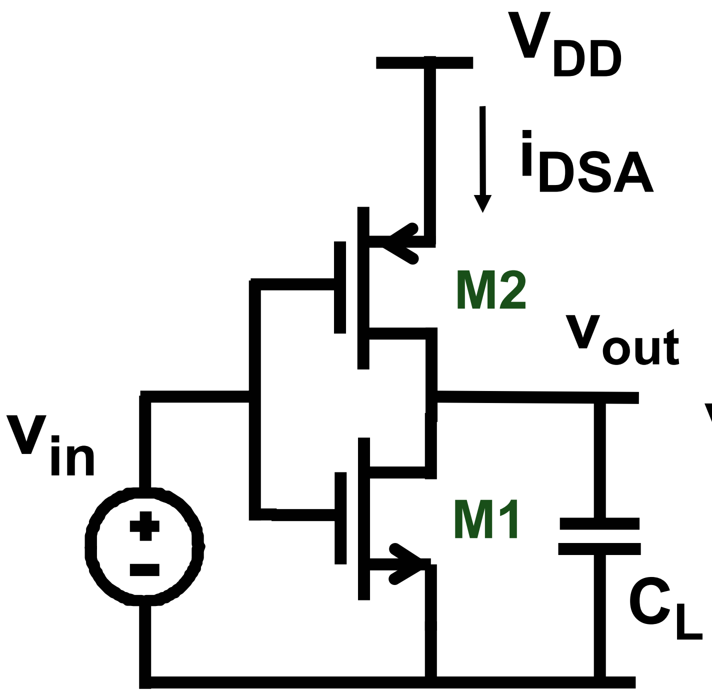
$$I_{DSn} = K'_n \frac{W_n}{L_n} (V_{in} - V_T)^2$$

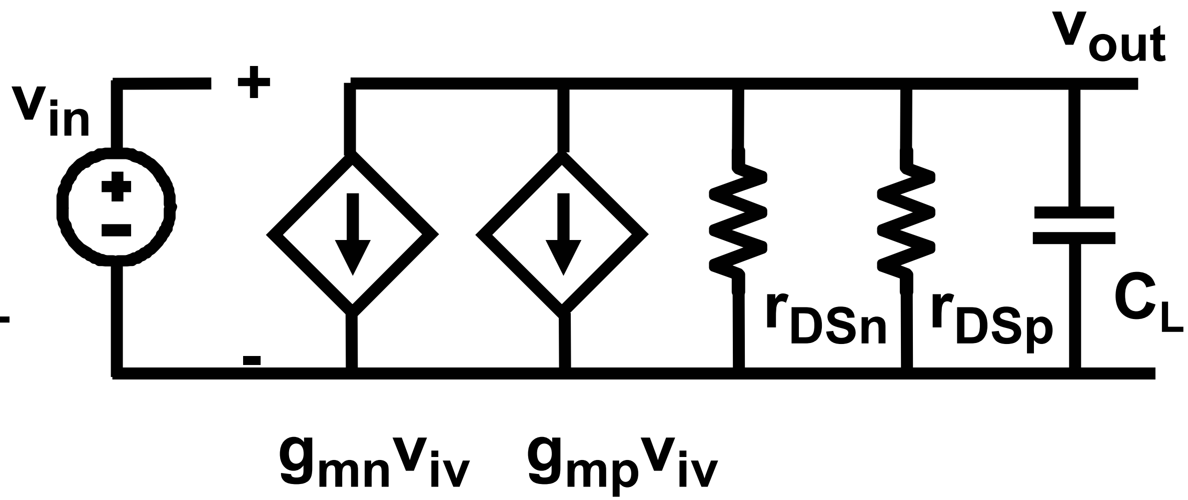
$$I_{DSp} = K'_p \frac{W_p}{L_p} (V_{DD} - V_{in} - V_T)^2$$

$$\Rightarrow K'_n \frac{W_n}{L_n} = K'_p \frac{W_p}{L_p}$$

$$I_{DS} = K'_n \frac{W_n}{L_n} \left(\frac{V_{DD}}{2} - V_T\right)^2$$

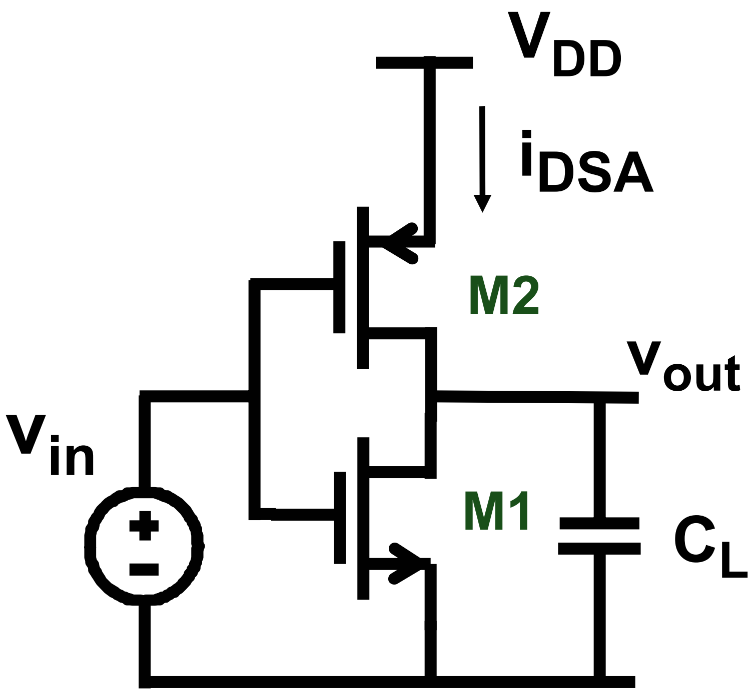
Analog amplifier : AC model





For the same I_{DS} en V_{GS}-V_T : $g_{mn} = g_{mp} = g_m$

Analog amplifier: AC gain Av



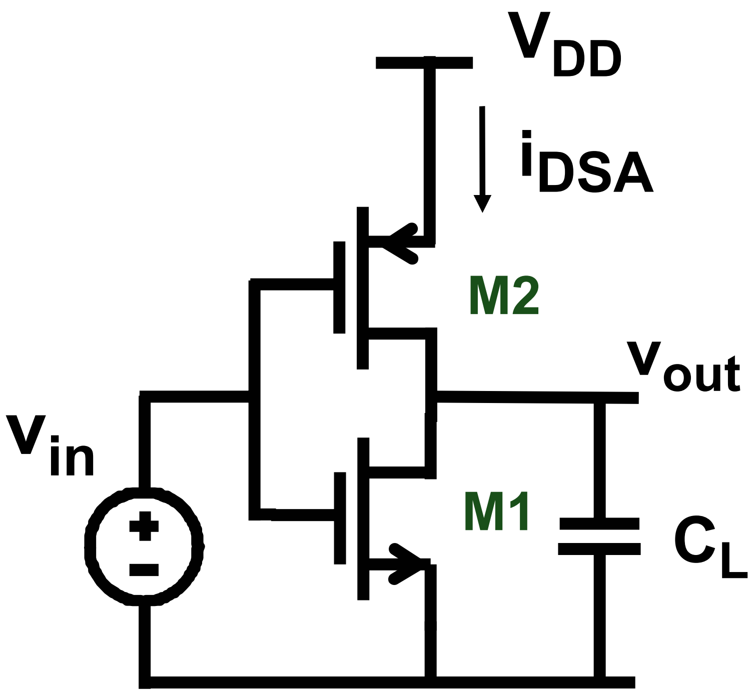
If $V_{En}L_n = V_{Ep}L_p = V_E$

$$g_{DSn} = g_{DSp} = g_{DS}$$

$$(g_{DS} = 1/r_{DS})$$

$$A_{v0} = -\frac{2g_m}{2g_{DS}} = -\frac{2V_E}{\frac{V_{DD}}{2} - V_T}$$

Analog amplifier : BW & GBW



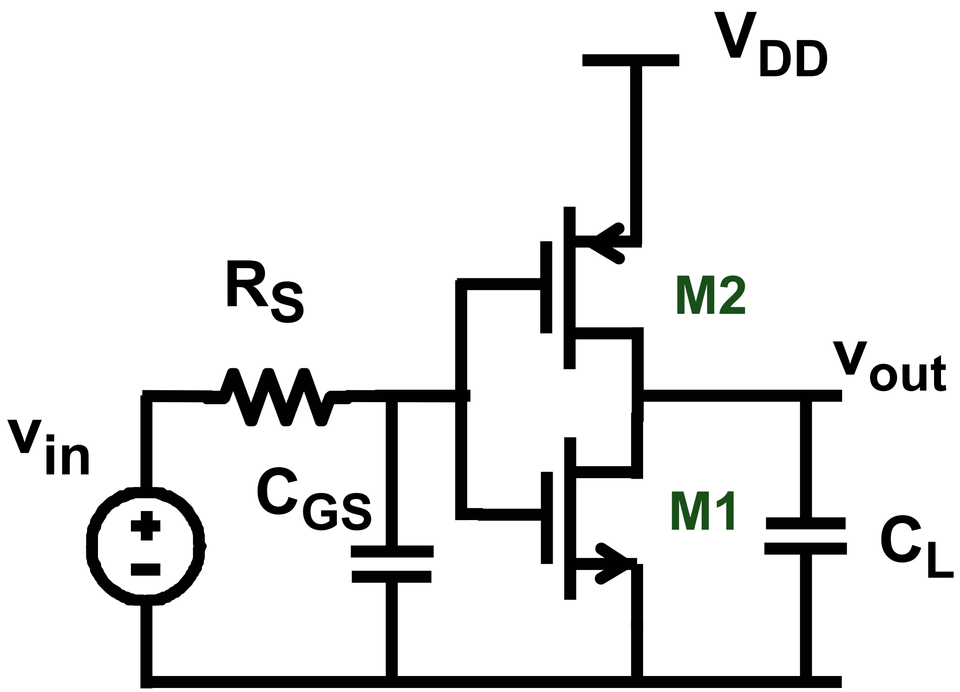
$$A_{v0} = 2g_m R_{out}$$

$$R_{out} = \frac{r_{DS}}{2}$$

$$BW = \frac{1}{2\pi\, R_{out} C_L}$$

$$GBW = \frac{2g_m}{2\pi\, C_L}$$

Analog amplifier: poles due to C_{GS}



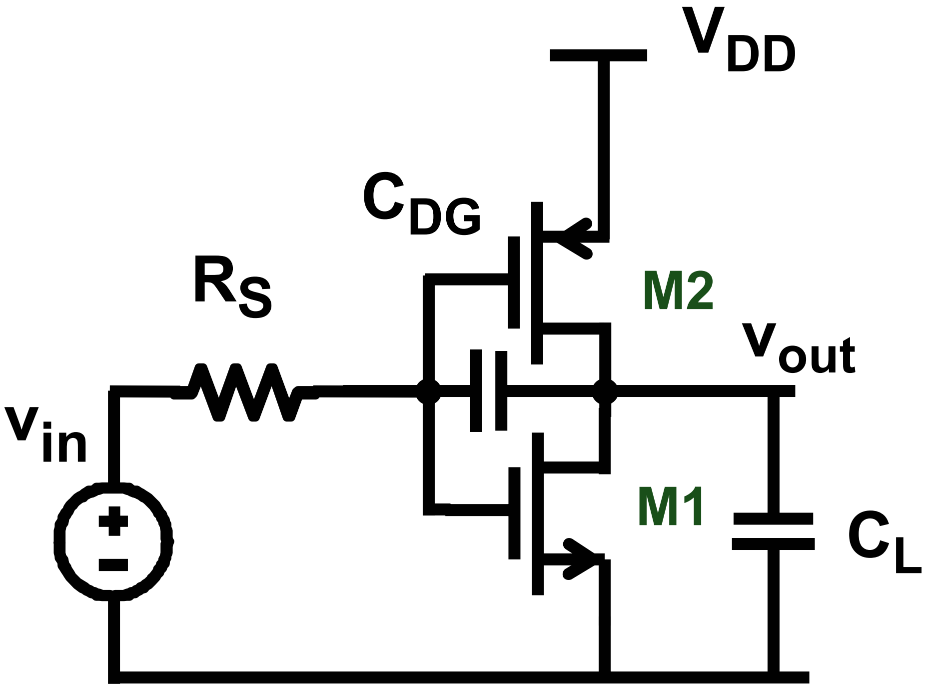
$$A_{v0} = 2g_m R_{out}$$

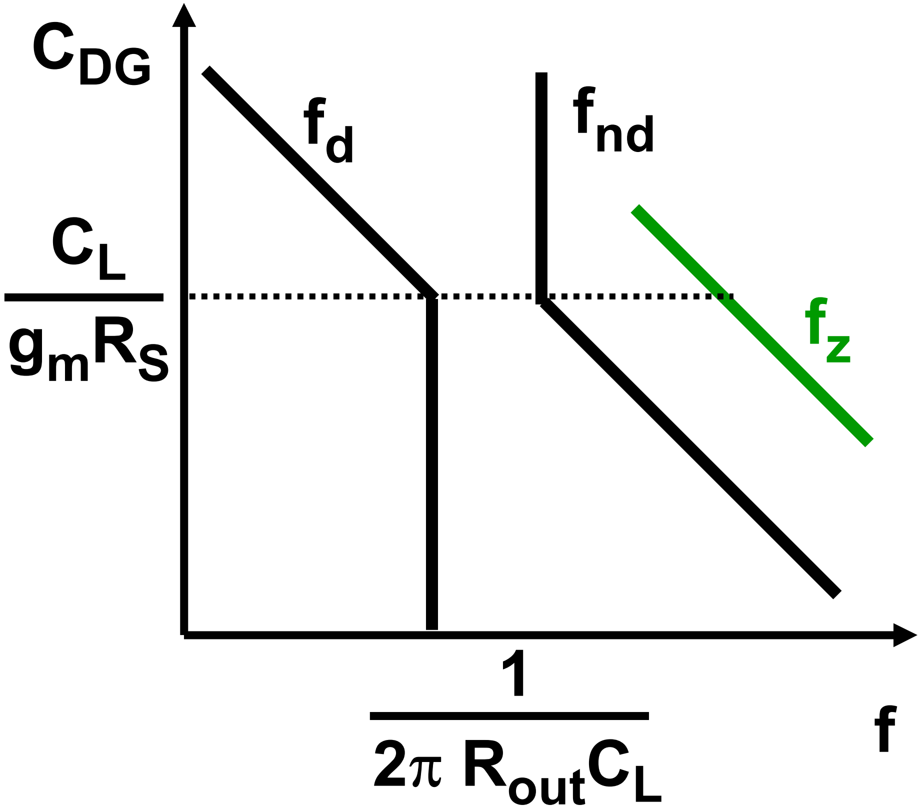
$$GBW = \frac{2g_m}{2\pi\, C_L}$$

$$C_{GSt} = C_{GS1} + C_{GS2}$$

But if $R_S C_{GSt} > r_{DS} C_L$: $GBW = f_T \dfrac{r_{DS}}{R_S}$

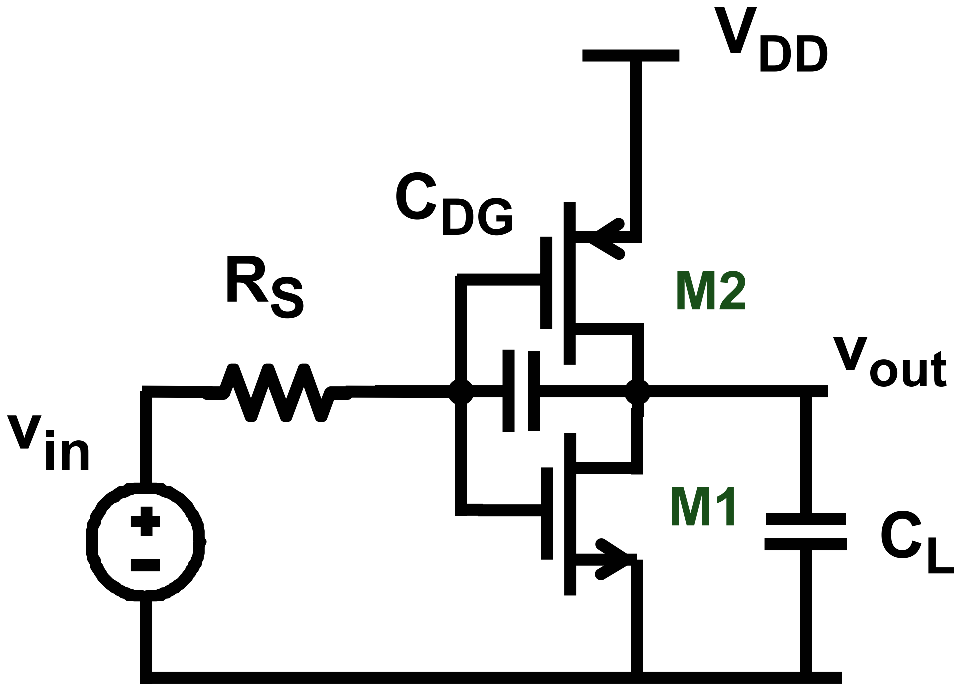
Analog amplifier: poles due to C_{DG}





$$\frac{v_{out}}{v_{in}} = \frac{A_{v0}\,(1 - sC_{DGt}/g_m)}{1 + s\,(R_{out}C_L + A_{v0}R_SC_{DGt}) + s^2 R_SR_{out}C_{DGt}C_L}$$

Analog amplifier: other poles



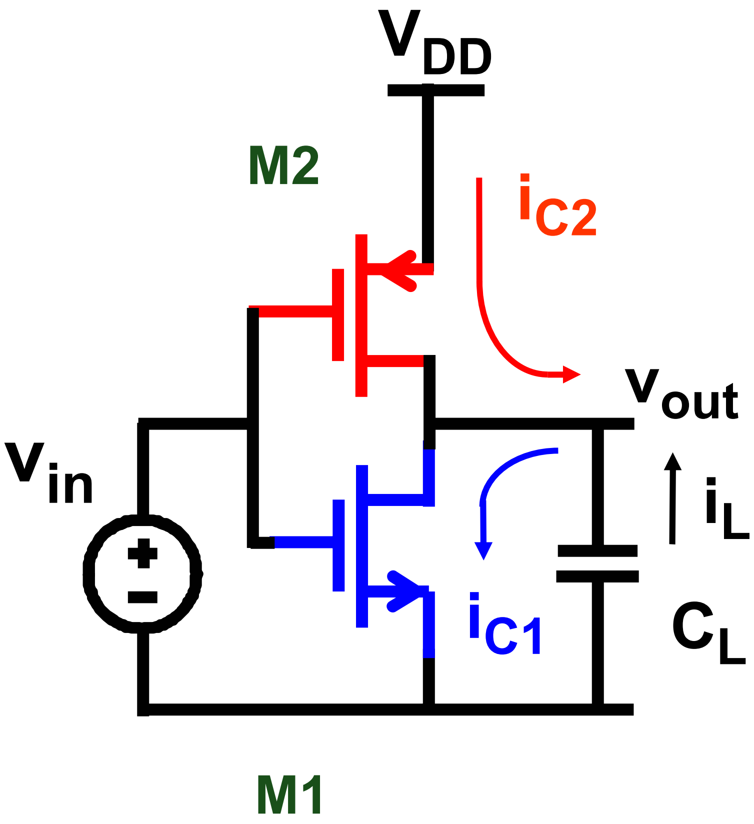
$$A_{v0} = 2g_m R_{out}$$

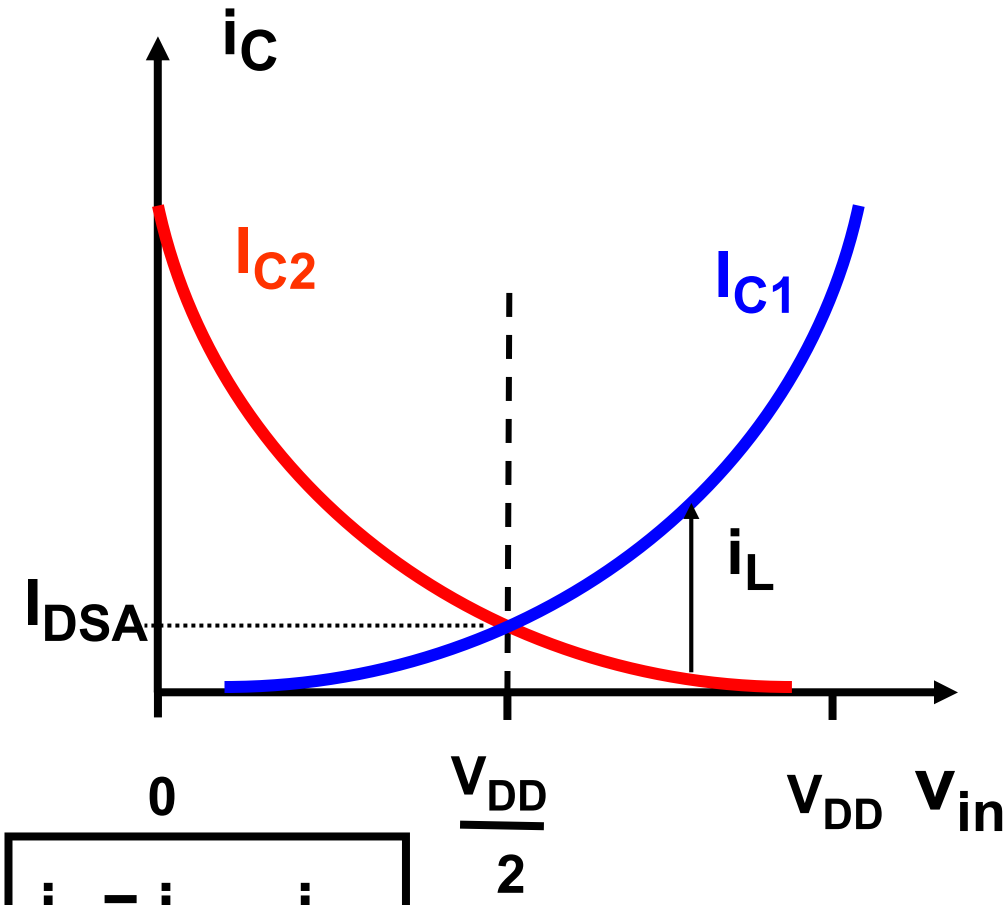
$$GBW = \frac{2g_m}{2\pi\, C_L}$$

$$C_{DGt} = C_{DG1} + C_{DG2}$$

But if $R_S C_{DGt} > \dfrac{1}{2\pi\, GBW}$: $GBW = \dfrac{1}{2\pi\, R_S\, C_{DGt}}$

Class AB operation





$$i_L = i_{C2} - i_{C1}$$

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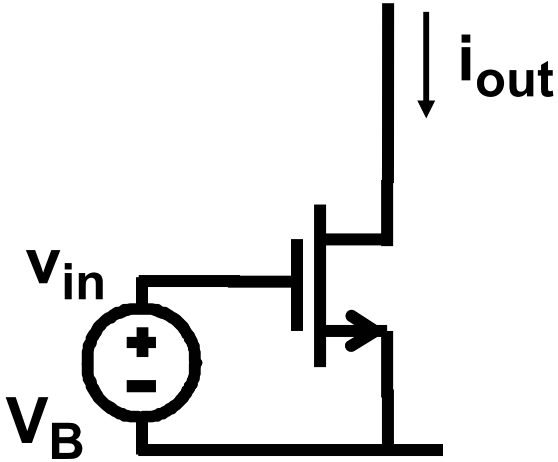
Single-transistor stages

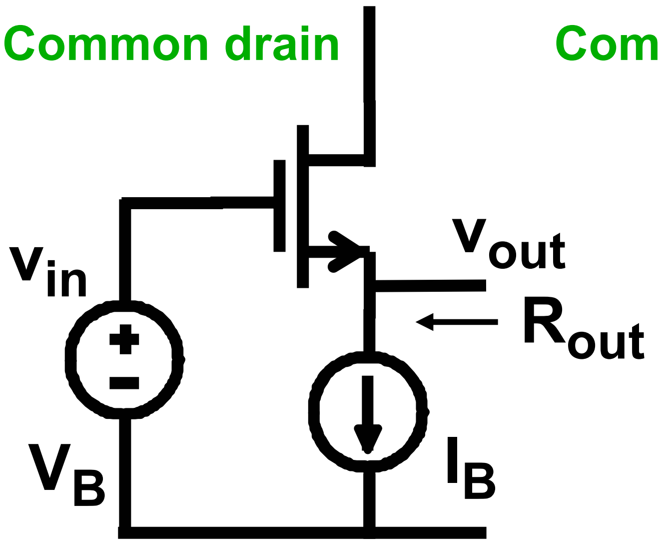
Common source



$$i_{out} = g_m v_{in}$$

Amplifier

Common drain



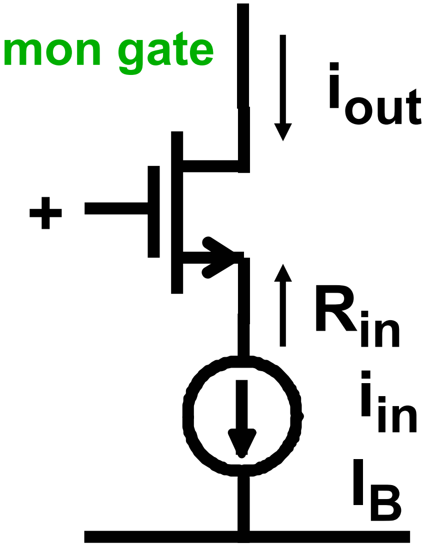
$$v_{out} = v_{in}$$

$$R_{out} \approx 1/g_m$$

Source follower

Voltage buffer

Common gate



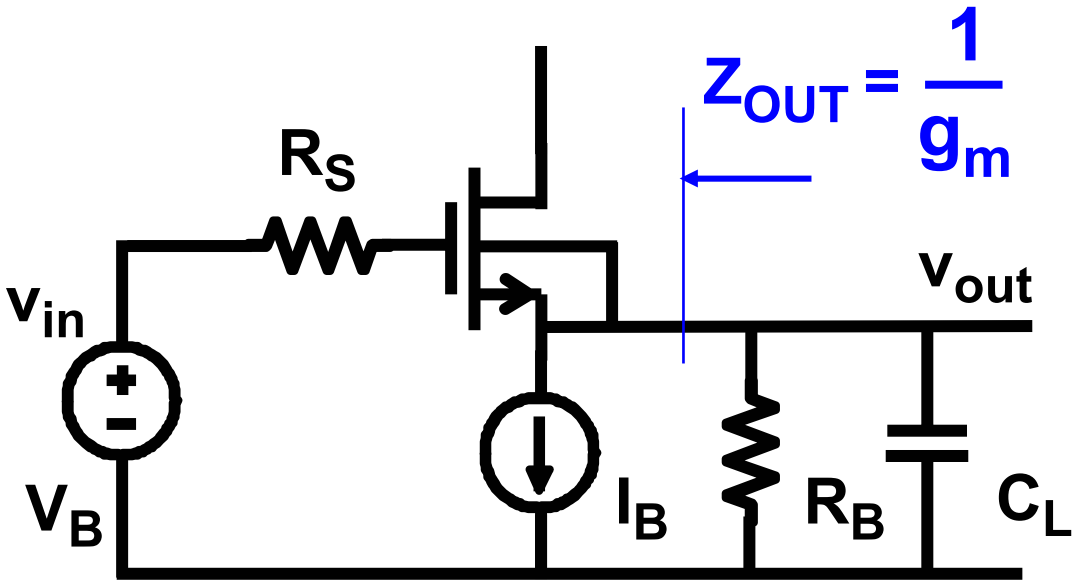
$$i_{out} = i_{in}$$

$$R_{in} \approx 1/g_m$$

Cascode

Current buffer

Source follower with $V_{BS} = 0$ (p-well)



$$V_{GS} = V_{T0} + \sqrt{\frac{I_B}{K'W/L}}$$

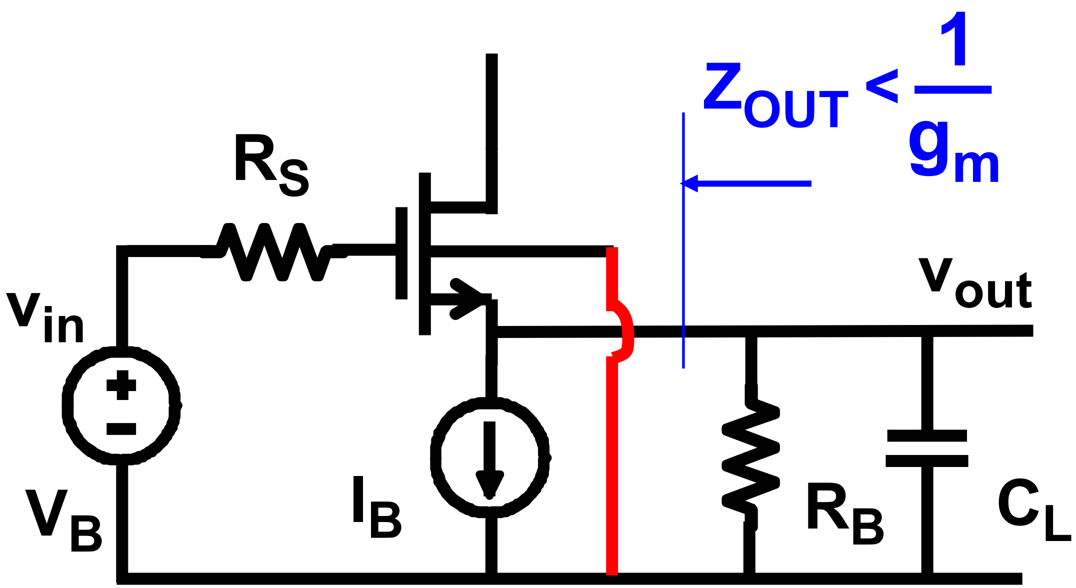
$V_{GS} = ct$ if $I_B = ct$

$$V_{OUT} = V_{IN} - V_{GS}$$

$$\Delta V_{OUT} = \Delta V_{IN}$$

$$A_v = 1$$

Source follower with $V_{BS} \neq 0$ (n-well)



$$V_{GS} = V_T + \sqrt{\frac{I_B}{K'W/L}}$$

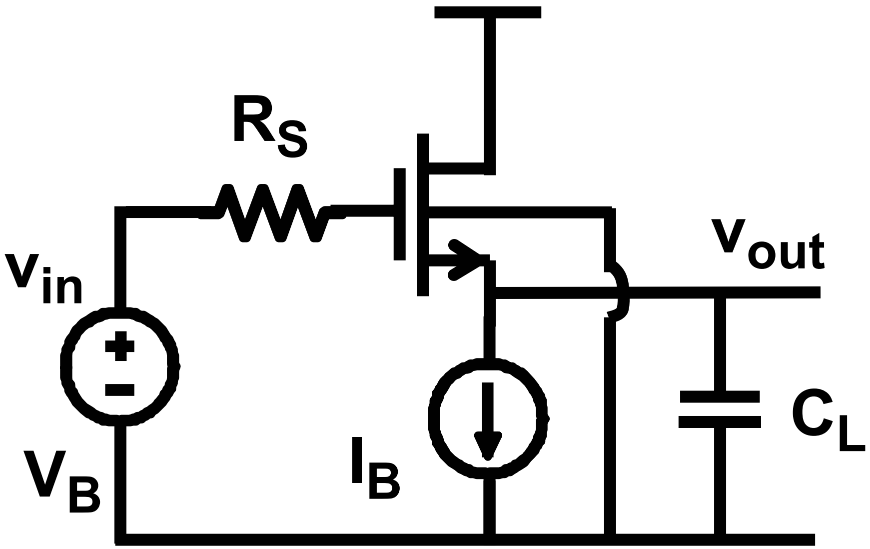
$$V_{GS} \neq ct$$

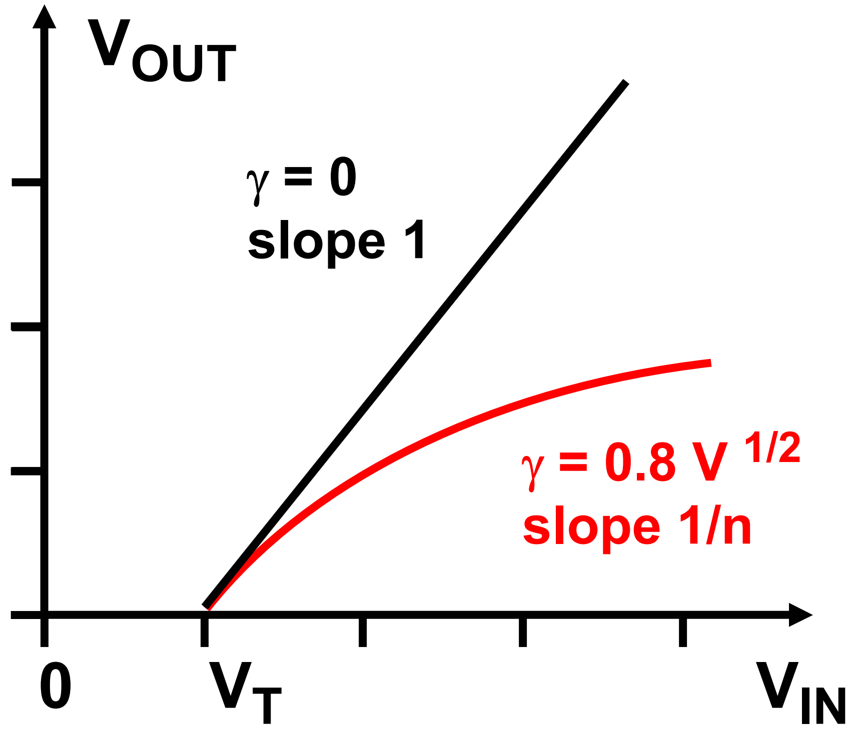
$$V_{OUT} = V_{IN} - V_{GS}$$

$$V_T = V_{T0} + \gamma \left[\sqrt{|2\Phi_F| + V_{OUT}} - \sqrt{|2\Phi_F|} \right]$$

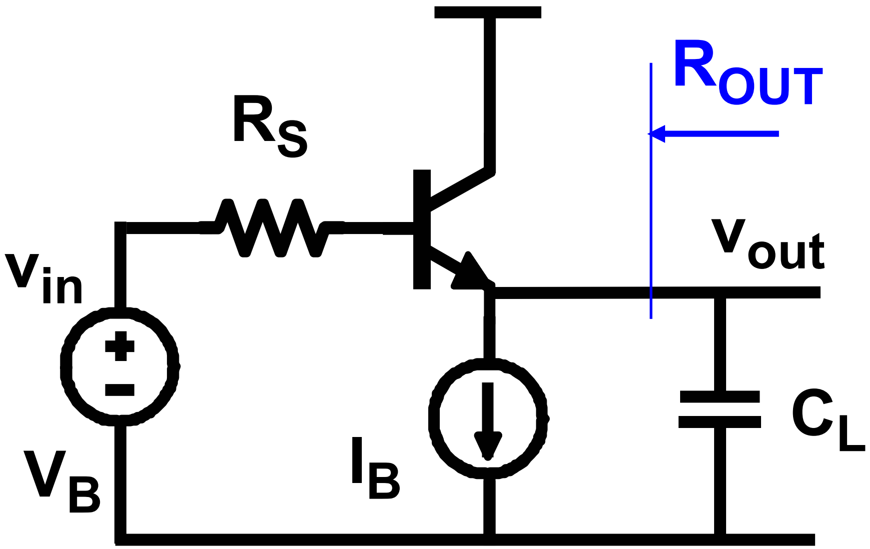
$$A_v = \frac{1}{n}$$

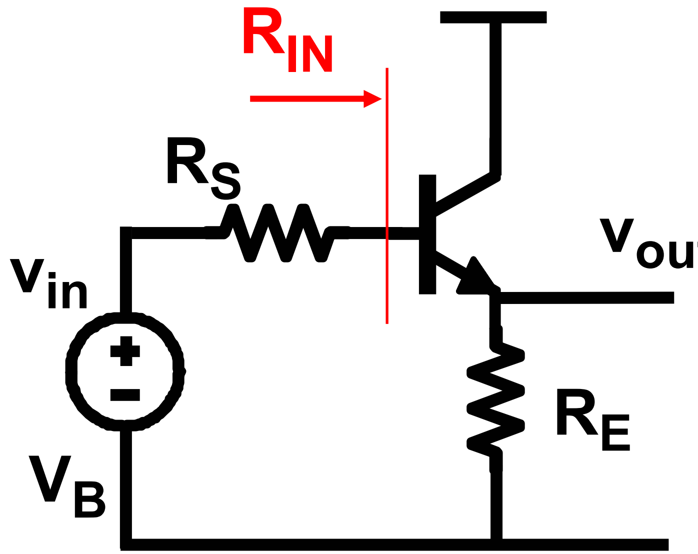
Source follower non-linearity





Emitter follower





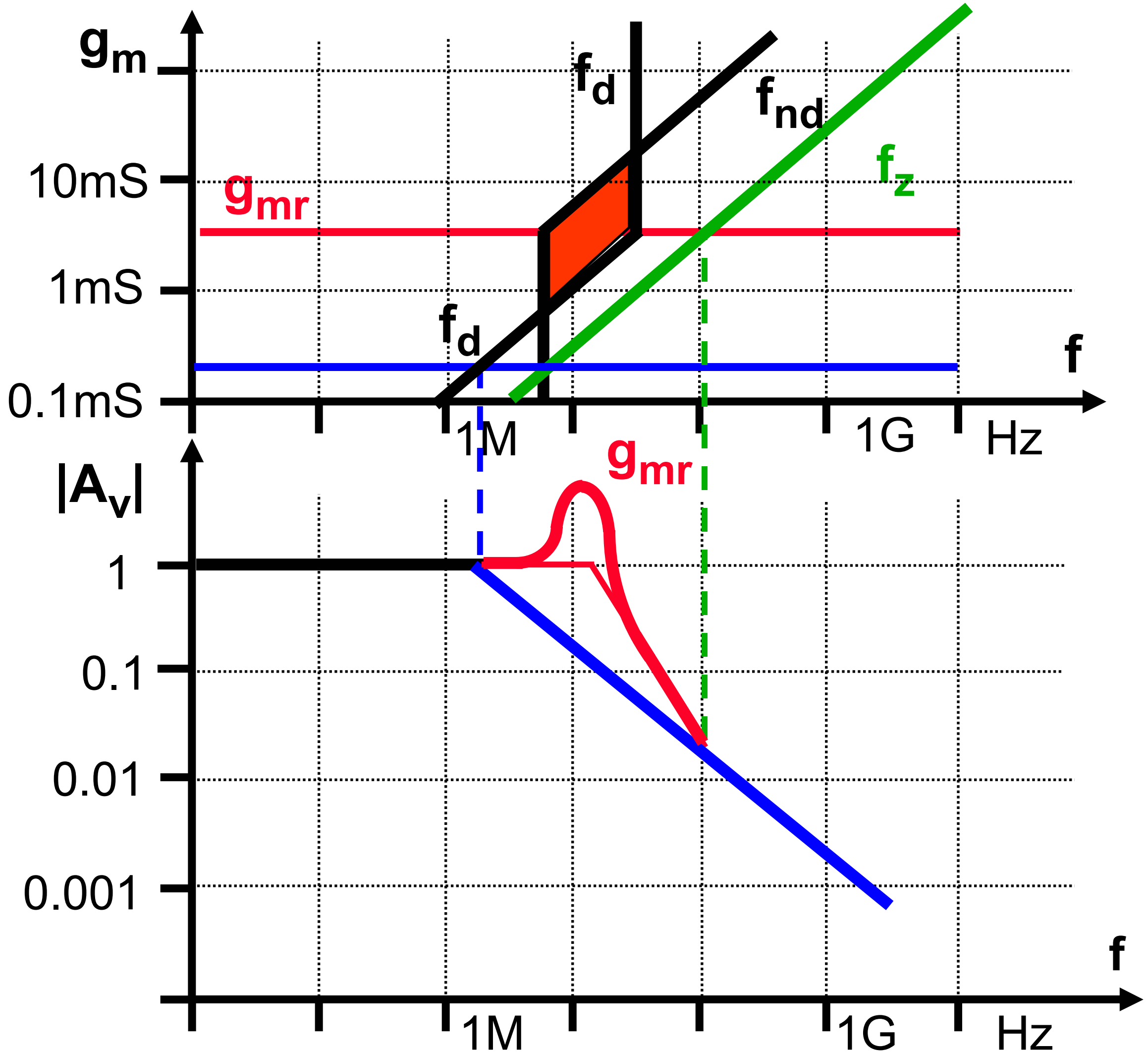
$A_v = 1$

$$R_{OUT} = \frac{1}{g_m} + \frac{R_S + r_B}{\beta+1}$$

$$R_{IN} = r_\pi + r_B + (\beta+1)R_E$$

Limited isolation !

Source follower with C_L load



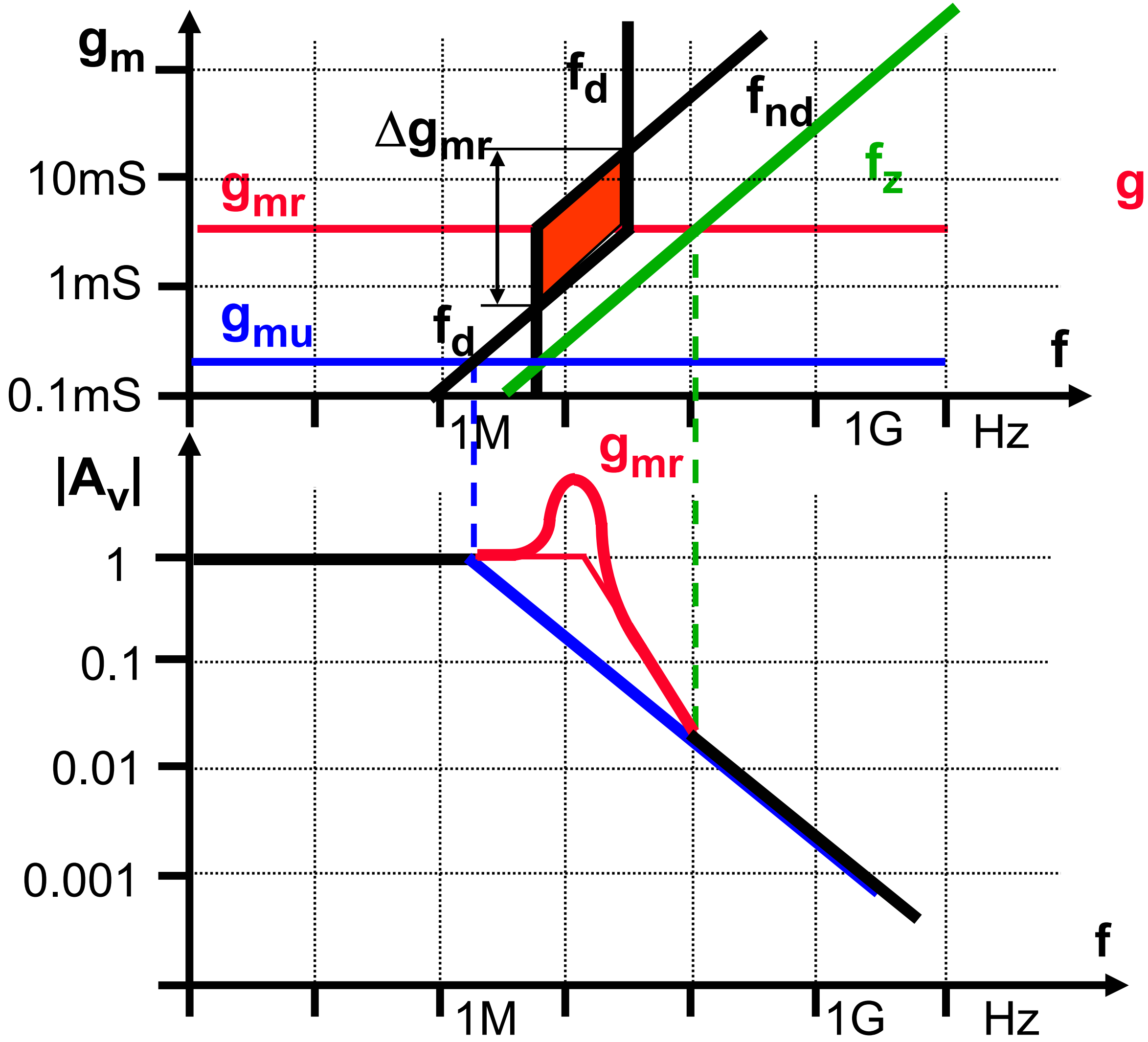
$$A_v = \frac{(1 + s\, C_{GS}/g_m)}{1 + s\,B + s^2\, C^2 R_S/g_m}$$

$$B = R_S C_{DG} + \frac{C'_{DS}}{g_m} + \frac{C_{GS}}{g_m}\left(1 + \frac{R_S}{r_{DS}}\right)$$

$$C^2 = C'_{DS} C_{DG} + C'_{DS} C_{GS} + C_{DG} C_{GS}$$

$$C'_{DS} = C_L + C_{DS}$$

Source follower with C_L load



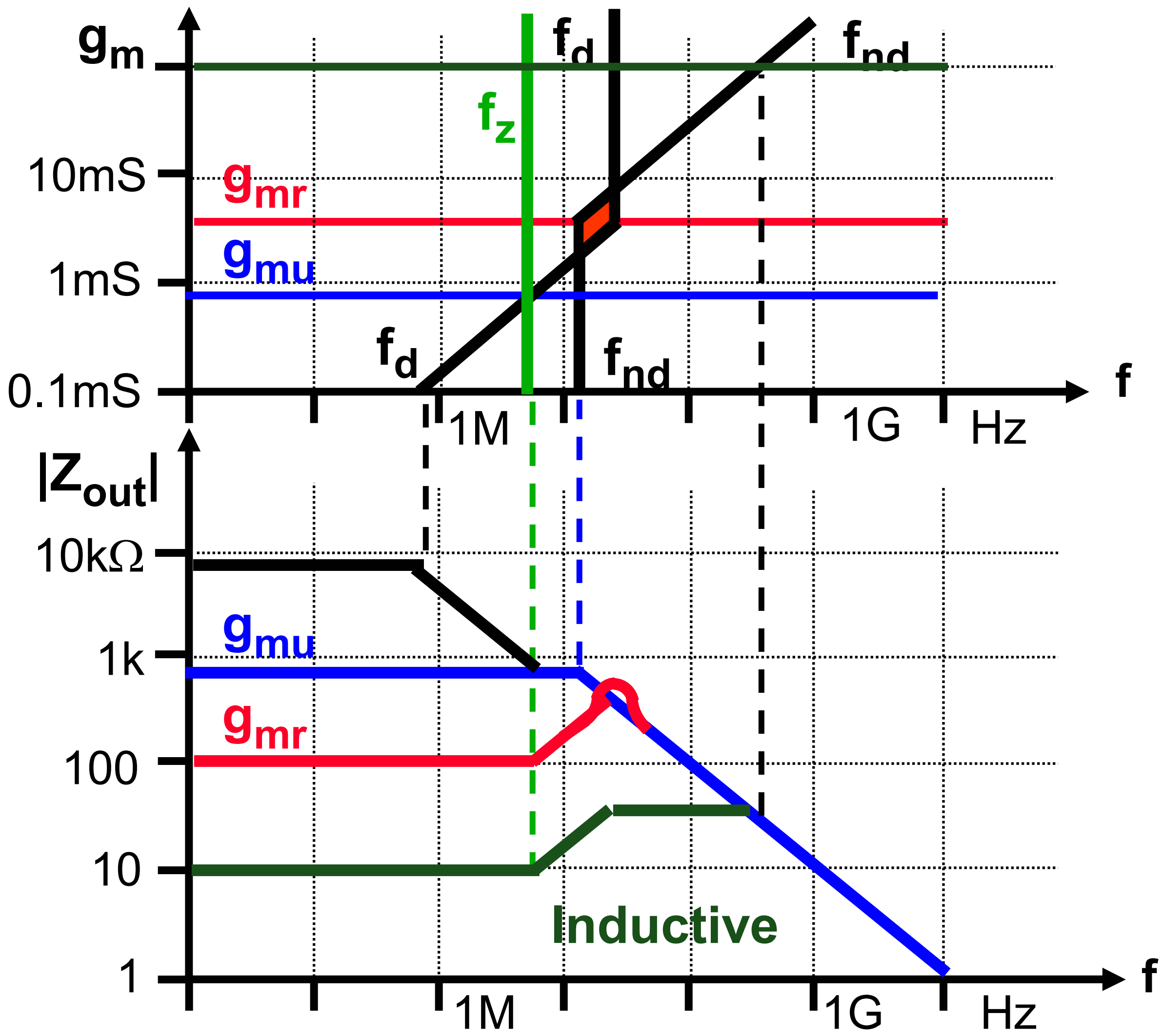
$$g_{mr} = \frac{1}{R_S} \frac{C_L + C_{DS} + C_{GS}}{C_{DG}}$$

$$\Delta g_{mr} = \frac{C_{DGt}}{C_{DG}}$$

$$C_{DGt} = \frac{C'_{DS}\,C_{GS}}{C'_{DS} + C_{GS}}$$

$$g_{mu} = \frac{1}{R_S}$$

Source follower : Output impedance



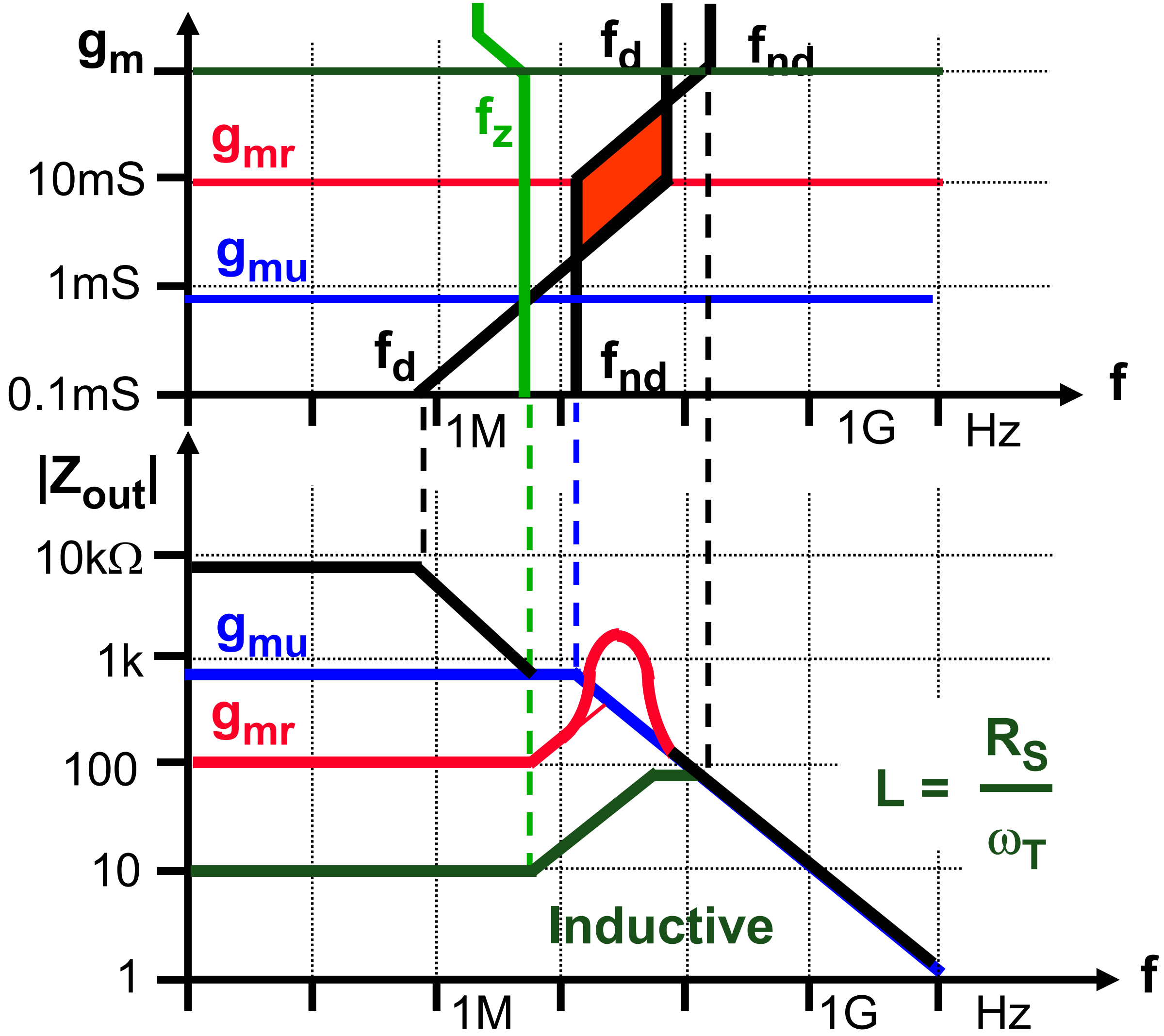
$$g_{mr} = \frac{1}{R_S} \frac{C_{GS} + C_{DS}}{C_{DG}}$$

$$g_{mu} \approx \frac{1}{R_S} \frac{C_{GS} + C_{DS}}{C_{GS} + C_{DG}}$$

$$f_z = \frac{1}{2\pi R_S C_{GS}}$$

$$f_{d,higm} = \frac{1}{2\pi R_S C_{DG}}$$

Emitter follower : Output impedance

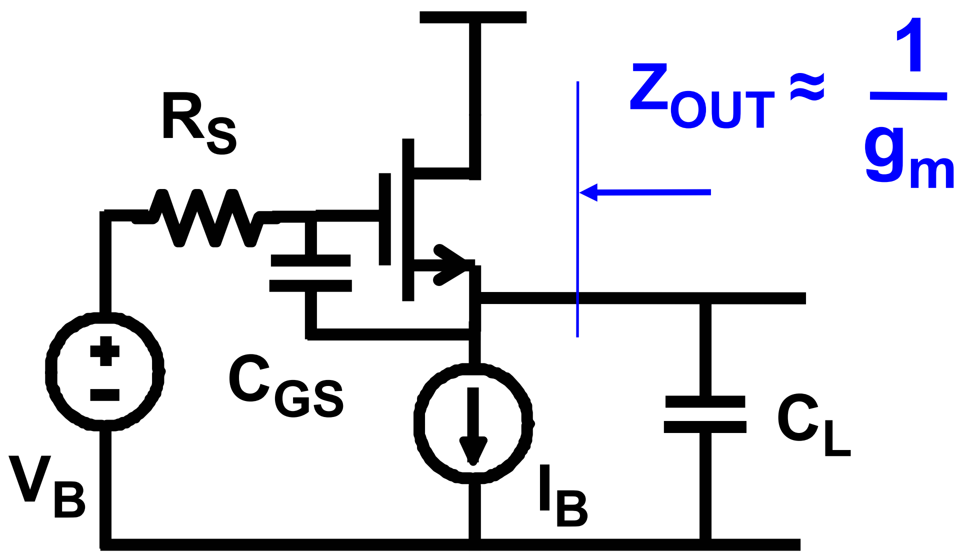


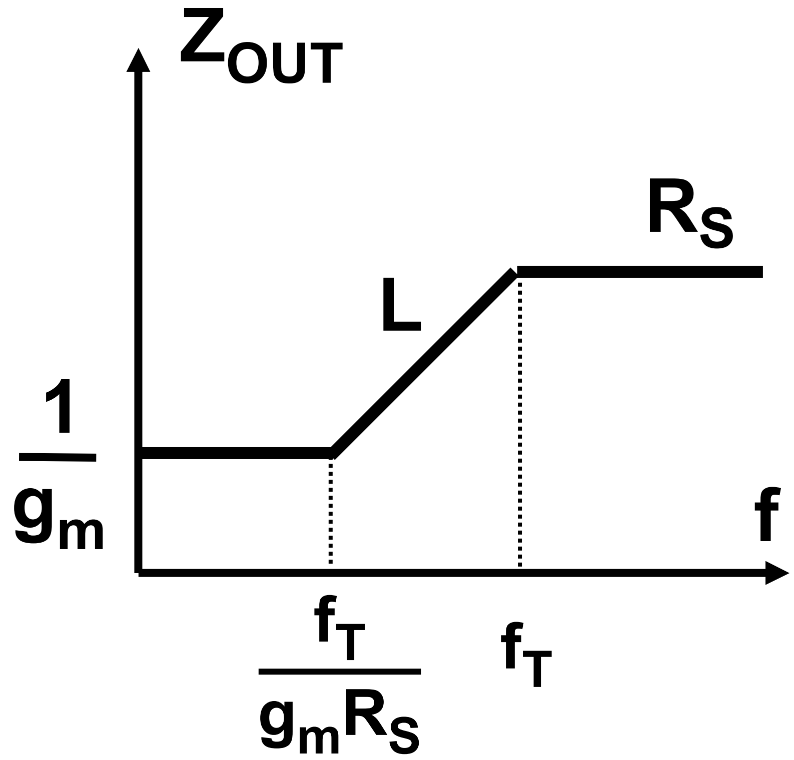
$$g_{mr} = \frac{1}{R_S}\,\frac{C_\pi + C_{CE}}{C_\pi + C_\mu}$$

$$g_{mu} \approx \frac{1}{R_S}\,\frac{C_{jE} + C_{CE}}{C_{jE} + C_\mu}$$

$$f_z = \frac{1}{2\pi\, R_S//r_\pi\, (C_\pi + C_\mu)}$$

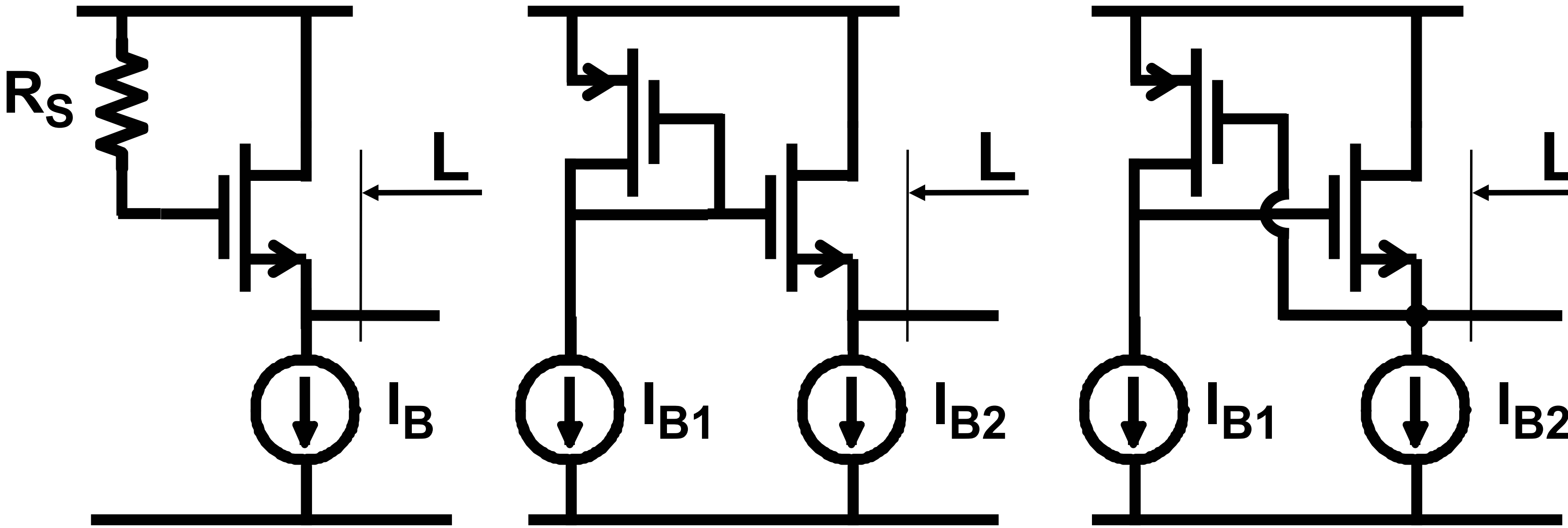
Source follower as active L





$$Z_{OUT} \approx \frac{1}{g_m}(1 + R_S C_{GS} s) \qquad L \approx \frac{R_S}{2\pi f_T} \text{ up to } f_T = \frac{g_m}{2\pi C_{GS}}$$

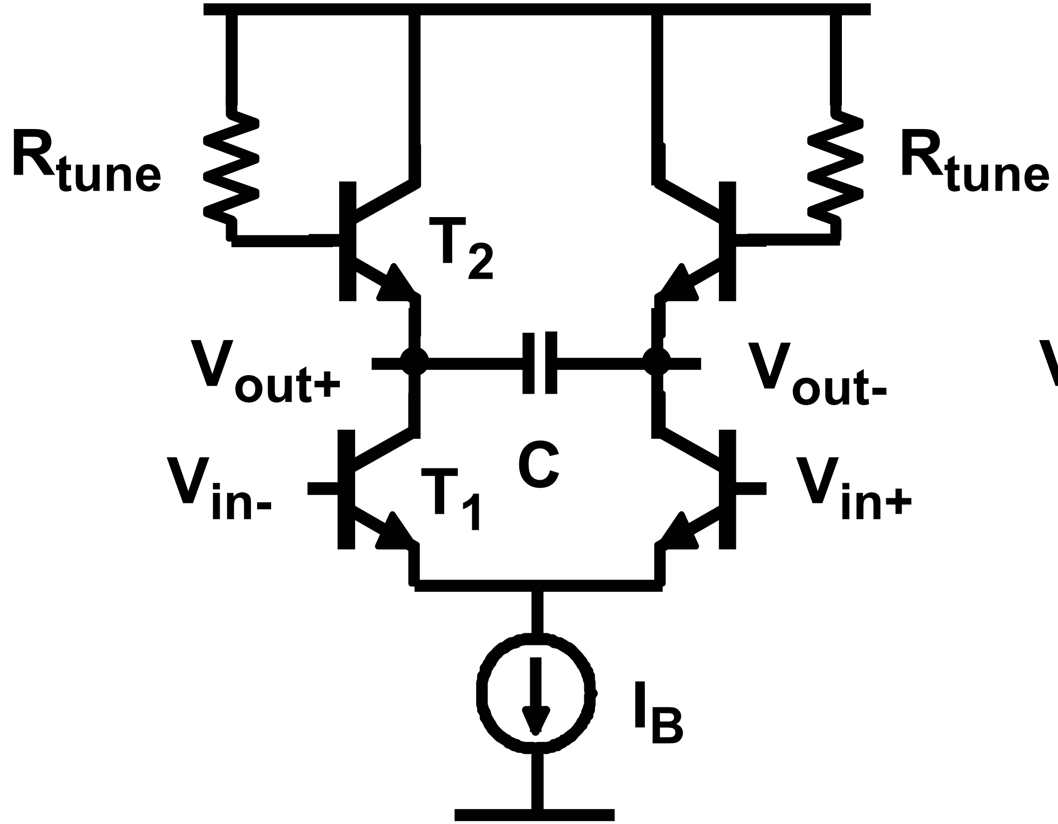
Source follower as active L



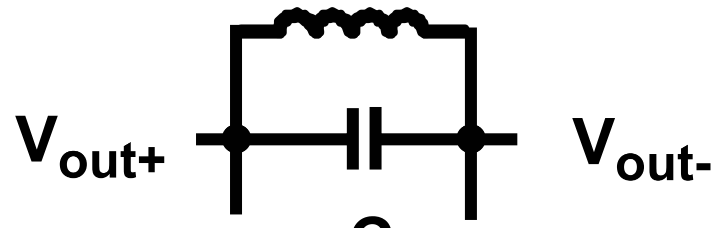
$$L \approx \frac{R_S}{2\pi f_T} \qquad L \approx \frac{1/g_{mp}}{2\pi f_{Tn}} \qquad L \approx \frac{1/g_{mp}}{2\pi f_{Tn}}$$

$$V_{DSn} = V_{GSn} \qquad V_{DSn} = V_{GSn} + V_{GSp} \qquad V_{DSn} = V_{GSp}$$

Floating inductor with parallel C



$$L = \frac{R_{tune}}{\omega_{T2}}$$



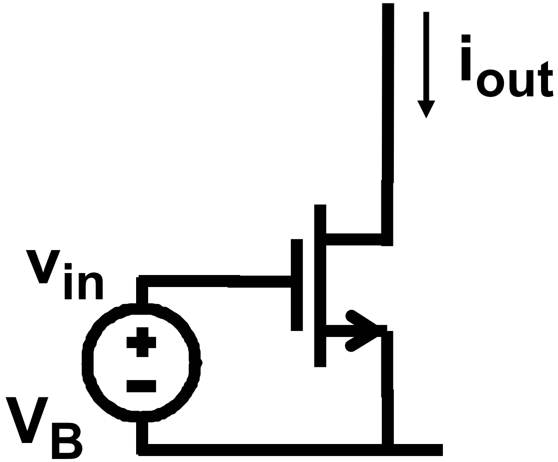
$$A_v = \frac{g_{m1}}{g_{m2}}$$

with HF peaking !

Table of contents

Single-transistor stages

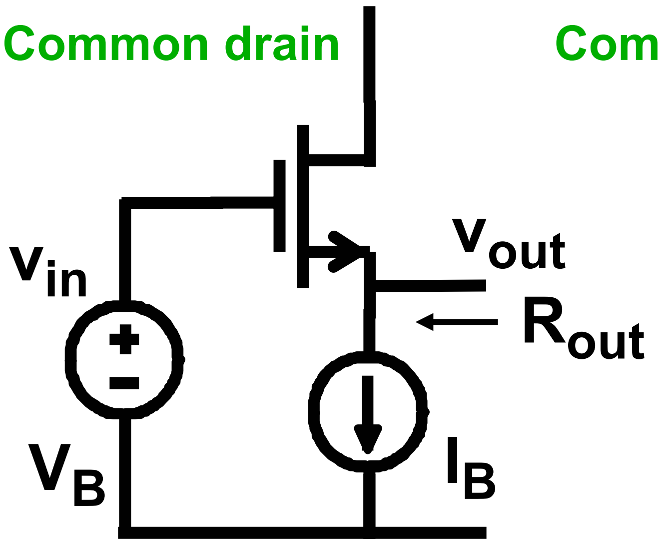
Common source



$$i_{out} = g_m v_{in}$$

Amplifier

Common drain



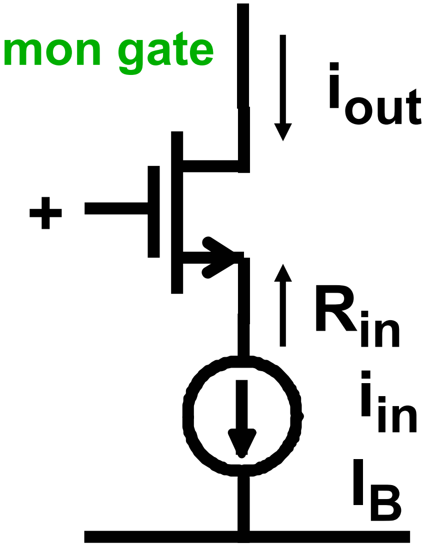
$$v_{out} = v_{in}$$

$$R_{out} \approx 1/g_m$$

Source follower

Voltage buffer

Common gate



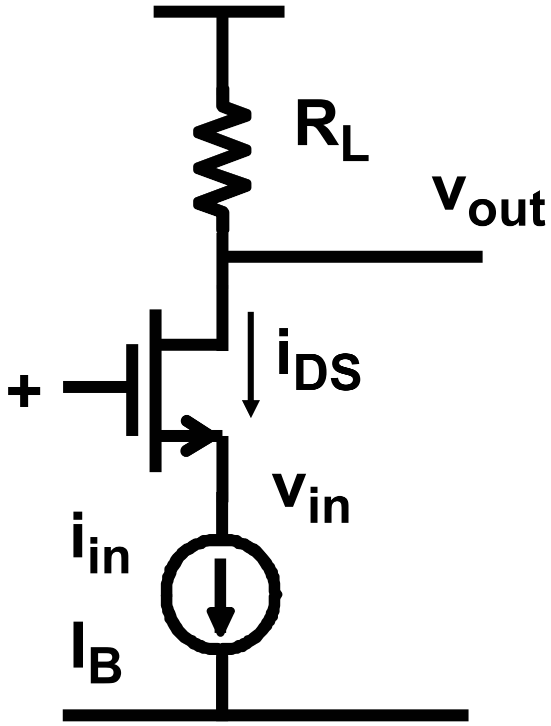
$$i_{out} = i_{in}$$

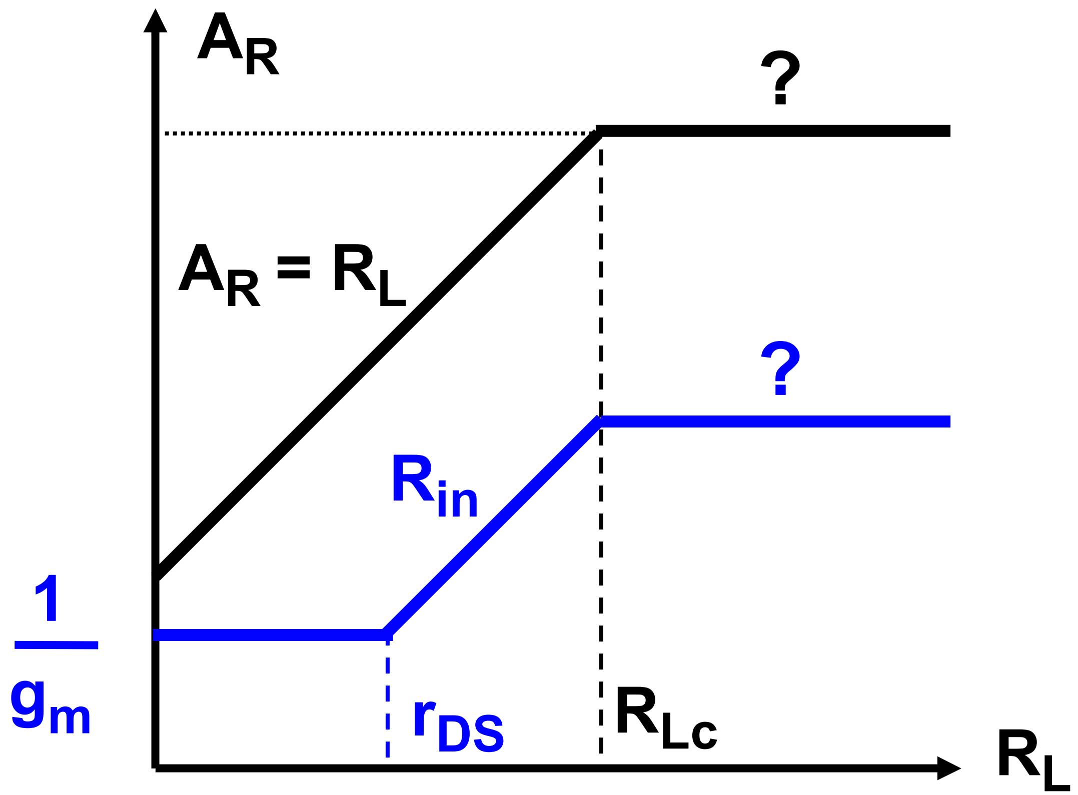
$$R_{in} \approx 1/g_m$$

Cascode

Current buffer

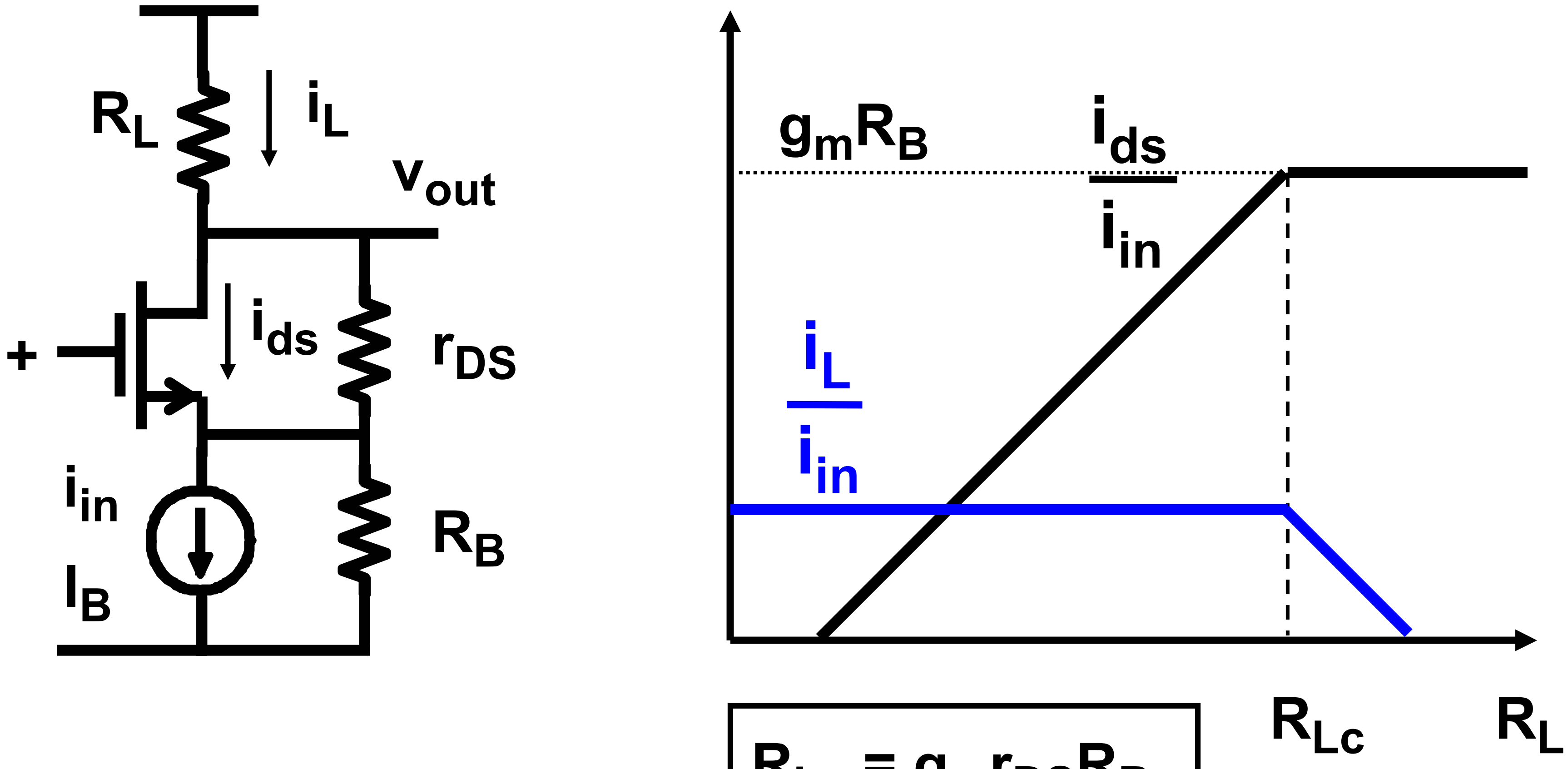
Cascode with resistive load





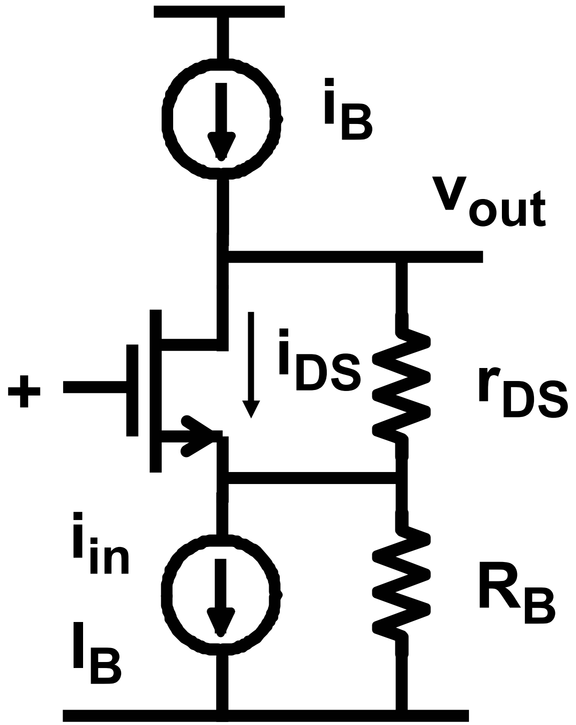
$$A_R = \frac{v_{out}}{i_{in}} \qquad R_{in} = \frac{v_{in}}{i_{in}}$$

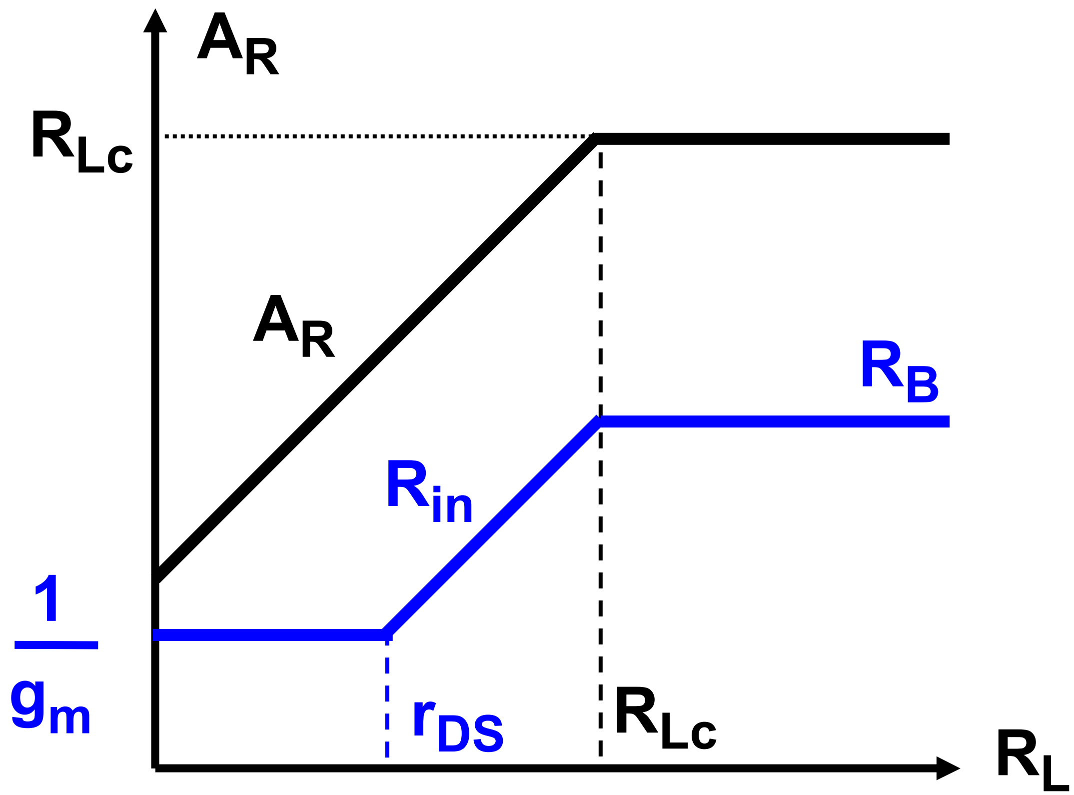
Cascode with resistive load



$$R_{Lc} = g_m r_{DS} R_B$$

Cascode with active load

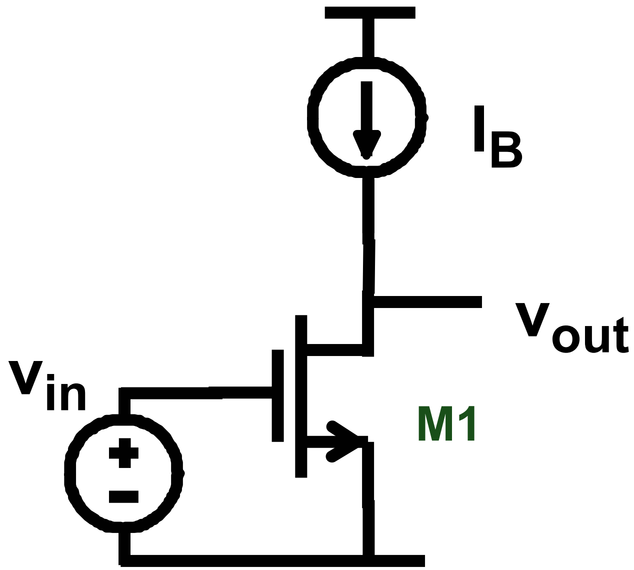


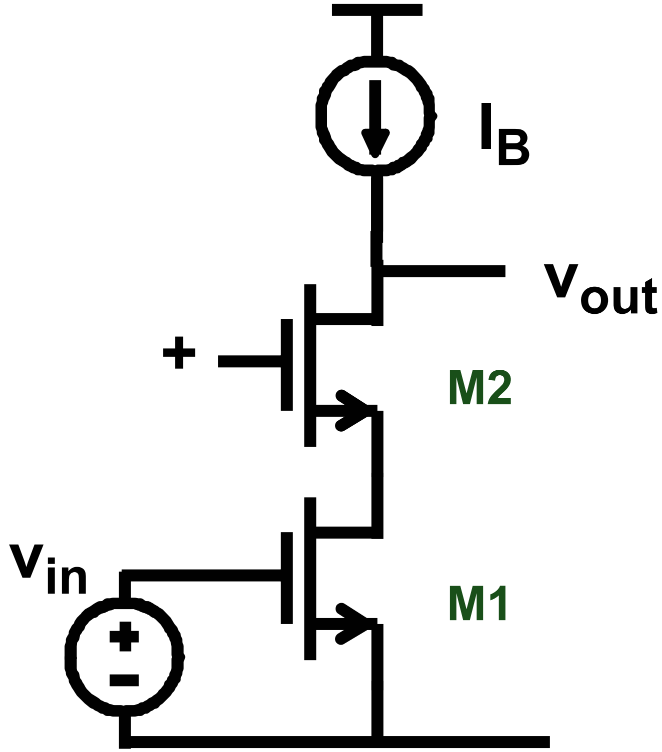


$A_R = \frac{v_{out}}{i_{in}}$ $R_{in} = \frac{v_{in}}{i_{in}}$

$R_{Lc} = g_m r_{DS} R_B$ $\approx 100\ R_B$

Cascode versus single-transistor





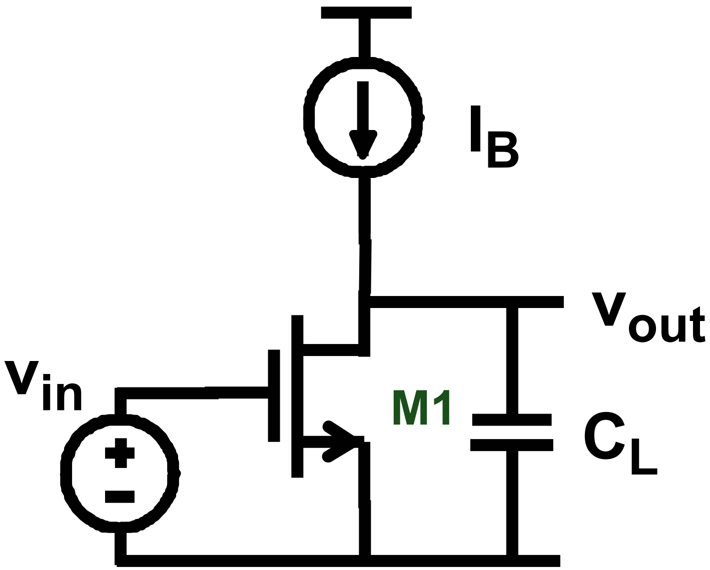
$A_v = (g_m r_{DS})_1$

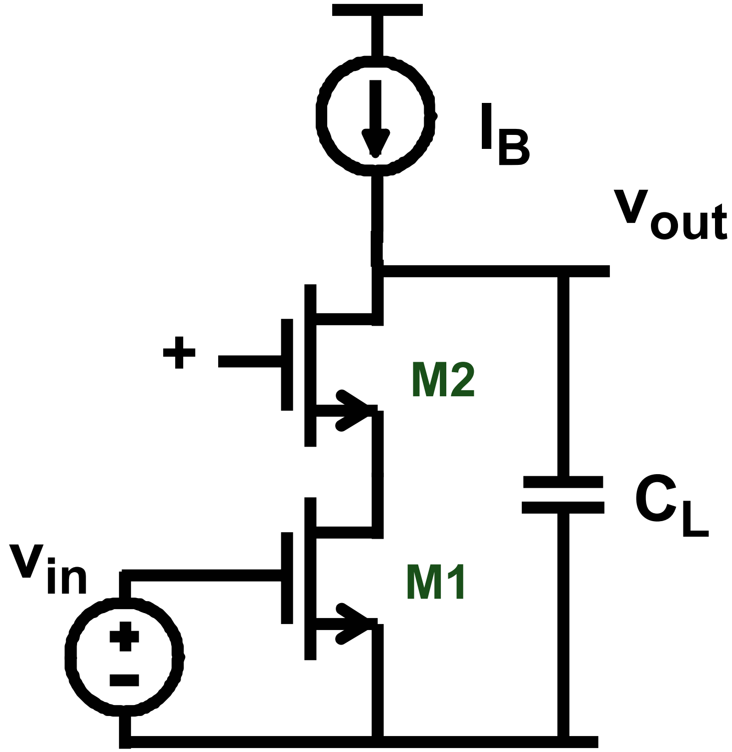
$R_{out} = r_{DS1}$

$A_v = (g_m r_{DS})_1 (g_m r_{DS})_2$

$R_{out} = r_{DS1} (g_m r_{DS})_2$

Cascode versus single-transistor



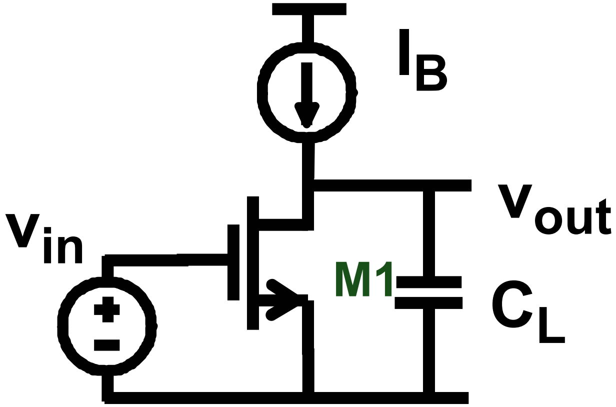


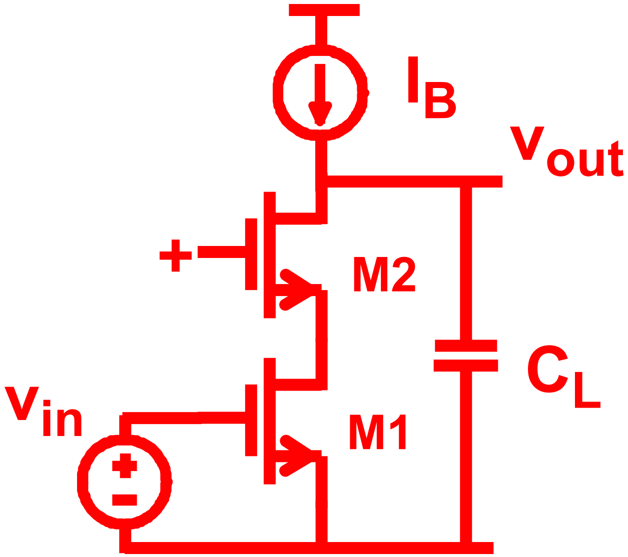
$$BW = \frac{1}{2\pi\ R_{out} C_L}$$

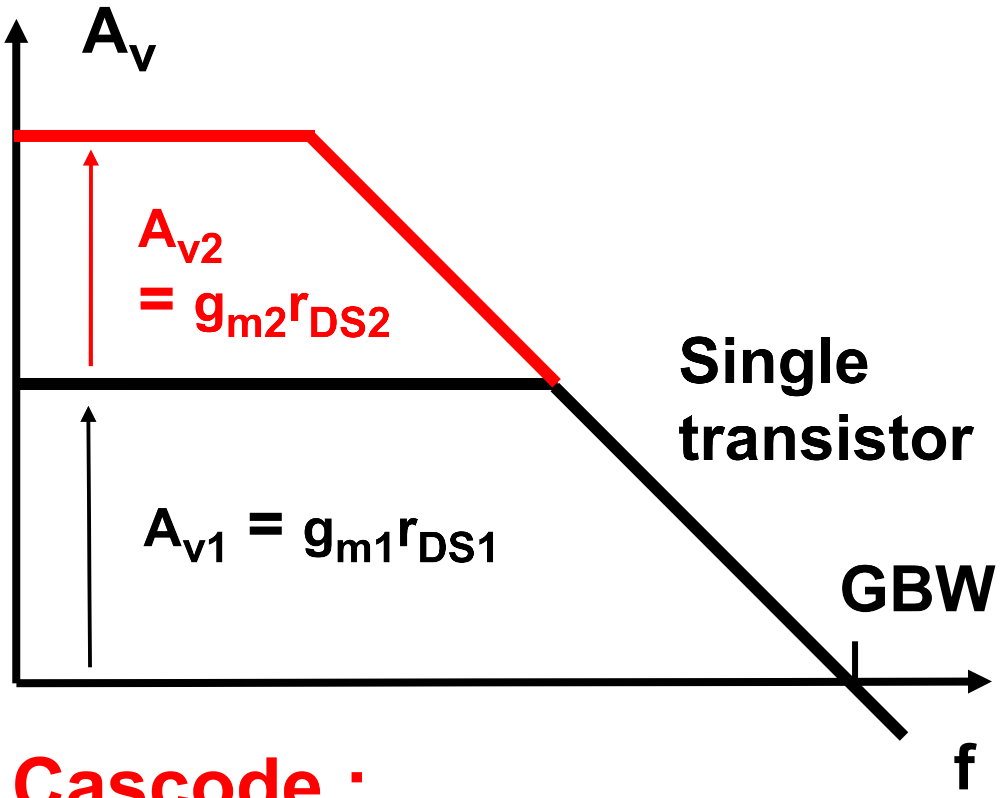
$$GBW = \frac{g_{m1}}{2\pi\ C_L}$$

for both !

Cascode versus single-transistor



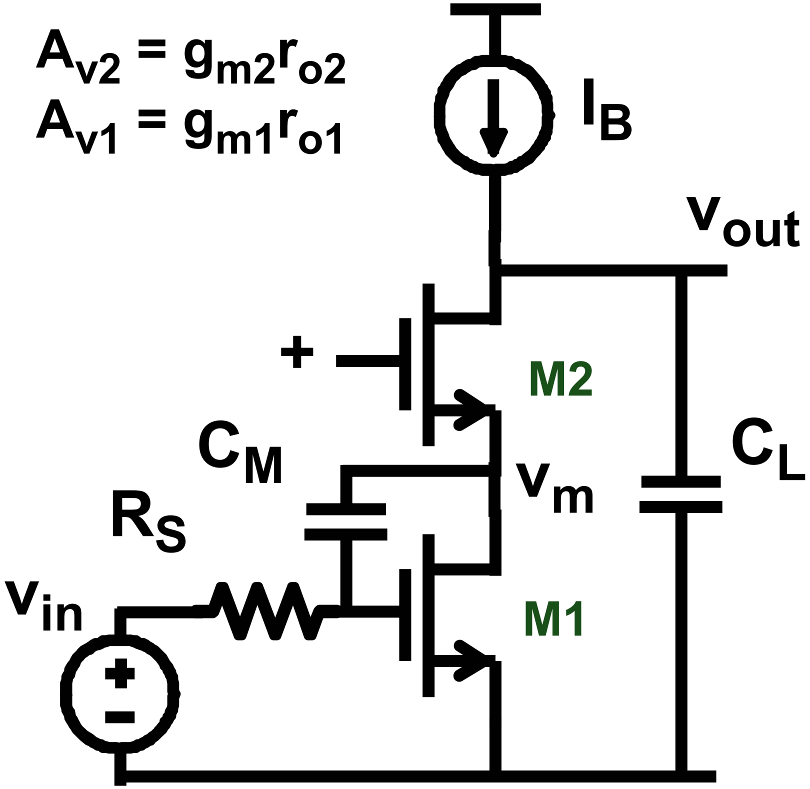


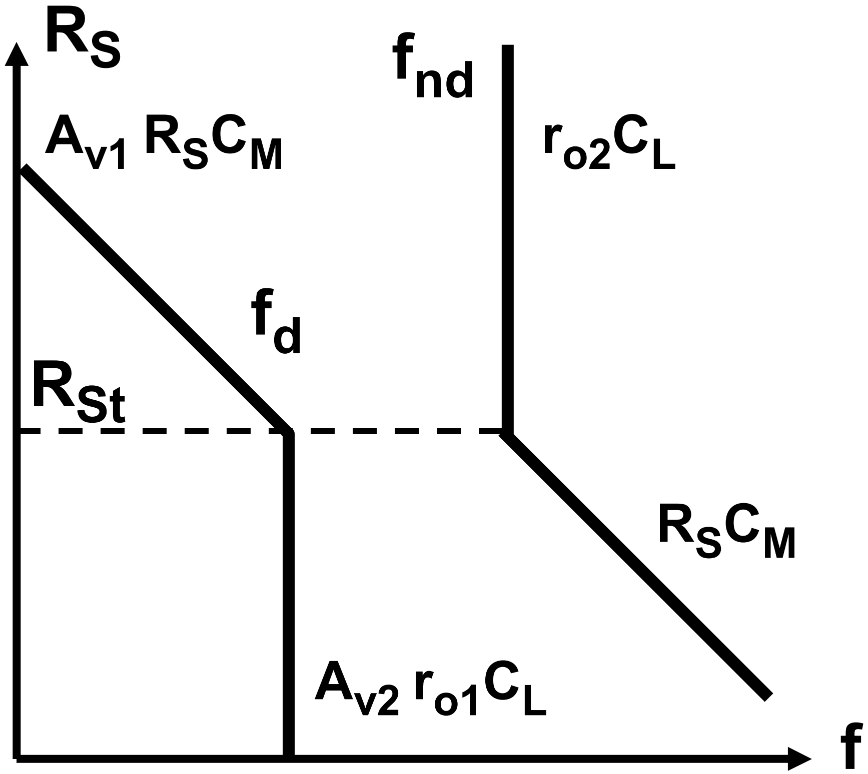


Cascode :
High gain
At low freq.

$$GBW = \frac{g_{m1}}{2\pi\ C_L}$$

Miller effect in cascode ?



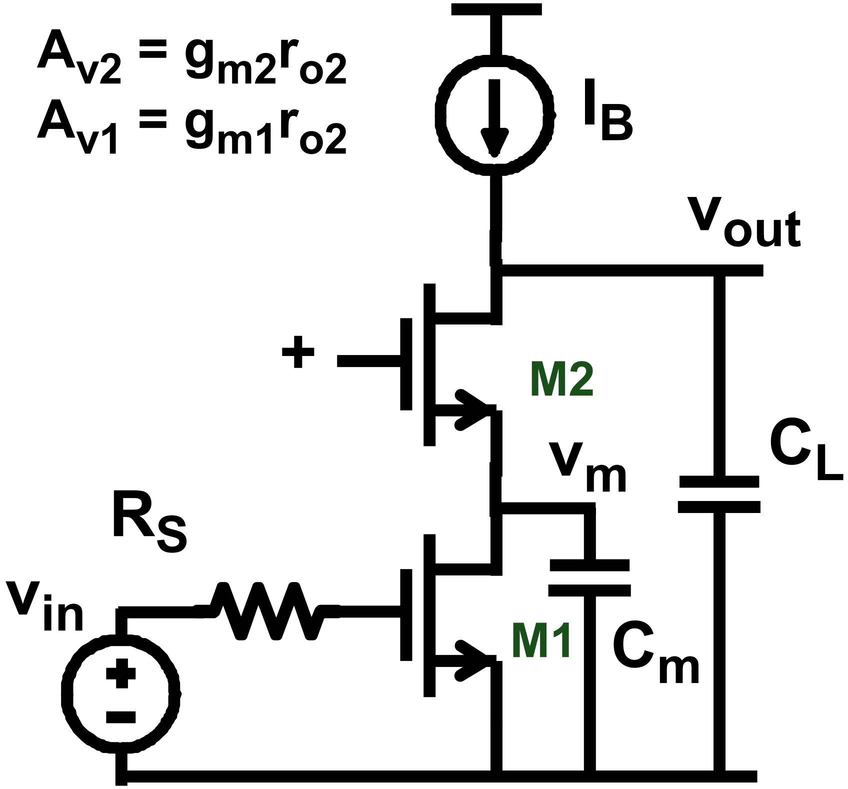


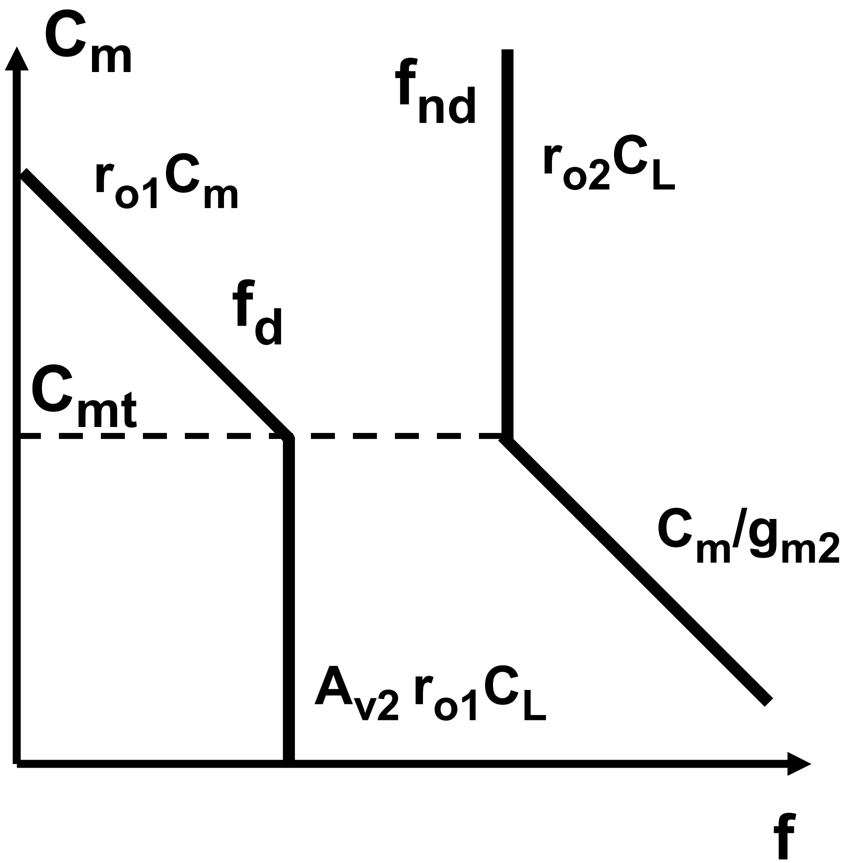
$$GBW = \frac{g_{m1}}{2\pi C_L}$$

No Miller if $R_S < R_{St} = r_{o2} \frac{C_L}{C_M} \frac{g_{m2}}{g_{m1}}$

Cascode with capacitance Cm at middle point

$A_{v2} = g_{m2} r_{o2}$
$A_{v1} = g_{m1} r_{o2}$

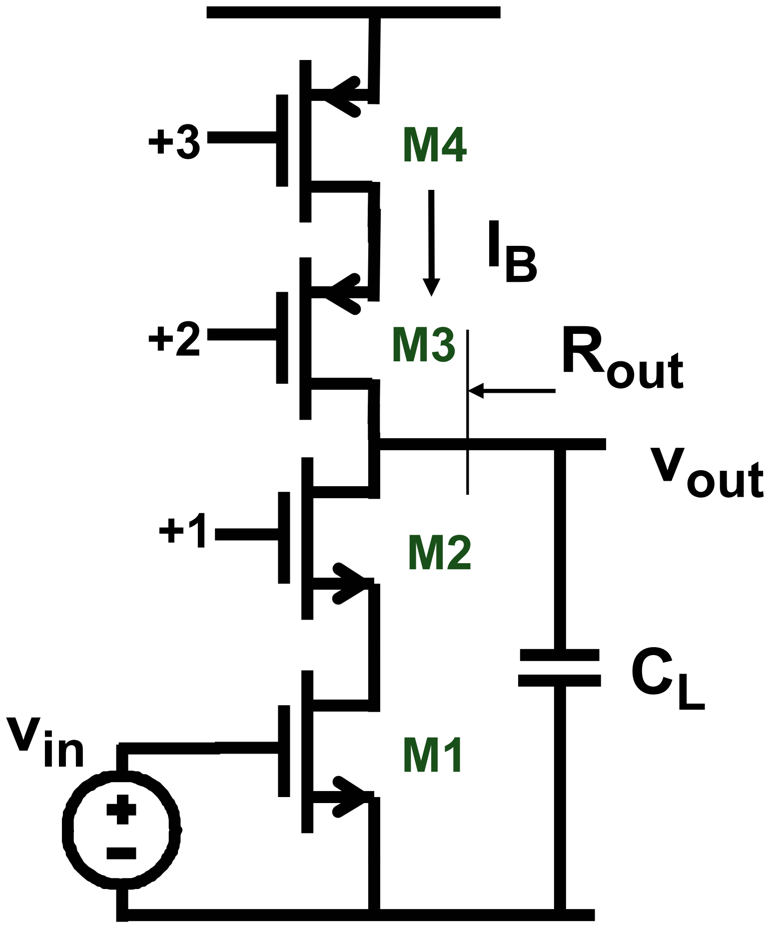




$$GBW = \frac{g_{m1}}{2\pi\ C_L}$$

$$C_{mt} = g_{m2} r_{o2}\ C_L = A_{v2}\ C_L$$

Telescopic Cascode



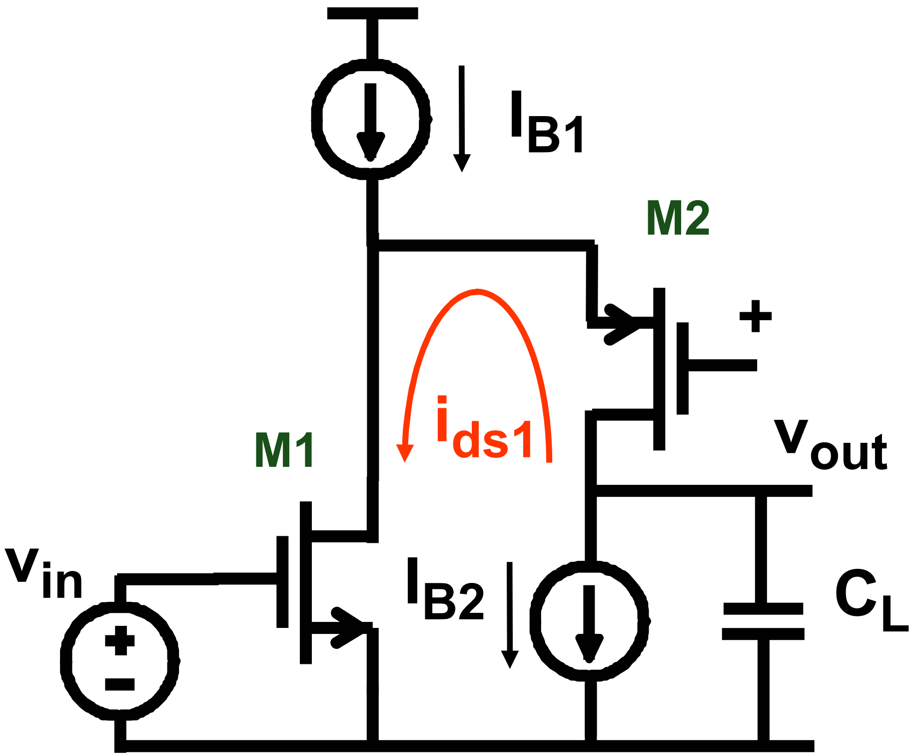
$$A_v = g_{m1} R_{out}$$

$$R_{out} = \frac{1}{2} r_{DS1}\, g_{m2}\, r_{DS2}$$

$$BW = \frac{1}{2\pi R_{out} C_L}$$

$$GBW = \frac{g_{m1}}{2\pi C_L}$$

Folded Cascode



$$I_{DS1} = I_{B1} - I_{B2} \approx I_{B1} / 2$$

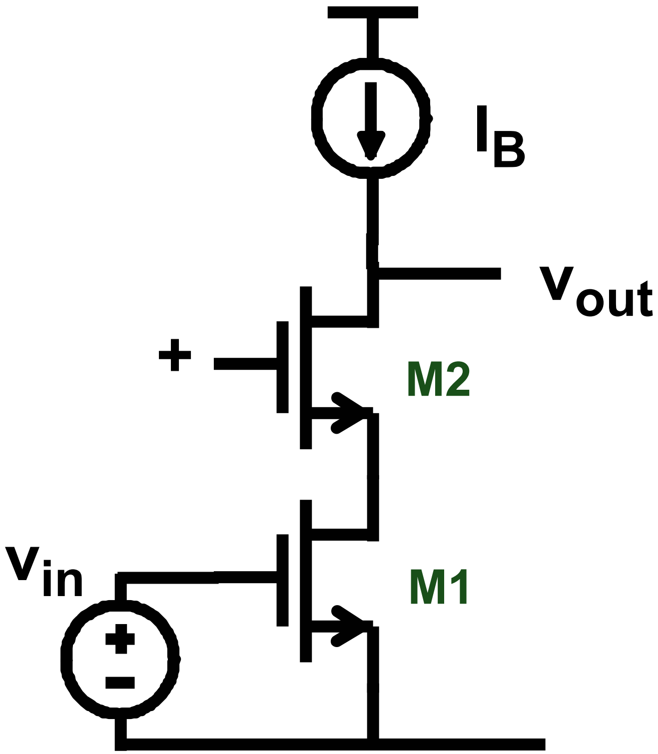
$$A_v = g_{m1} R_{out}$$

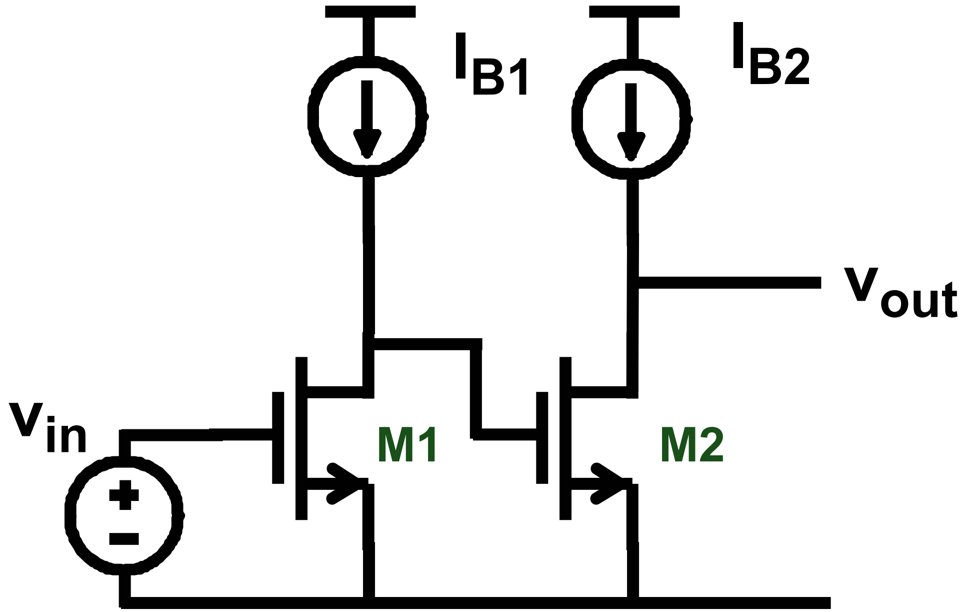
$$R_{out} = r_{DS1}\, g_{m2}\, r_{DS2}$$

$$BW = \frac{1}{2\pi R_{out} C_L}$$

$$GBW = \frac{g_{m1}}{2\pi C_L}$$

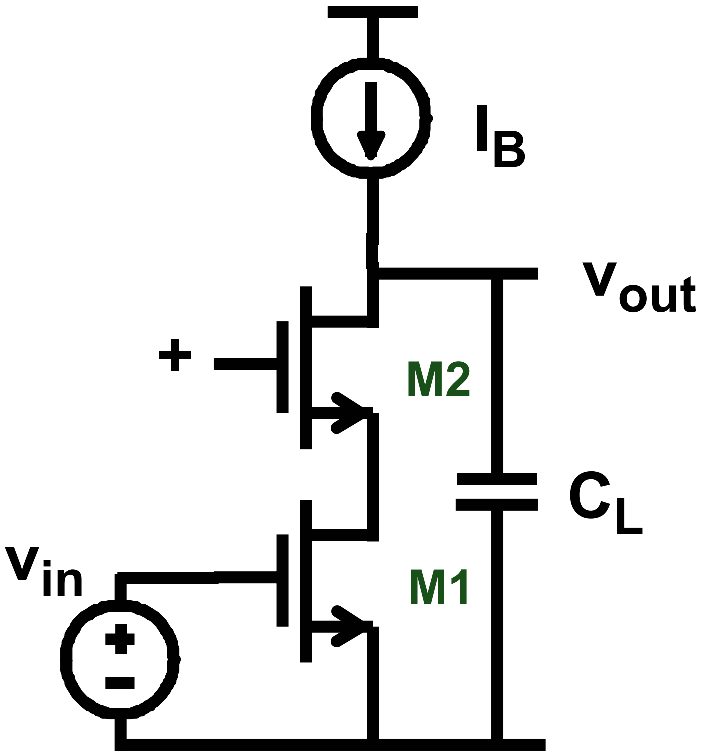
Cascode versus cascade





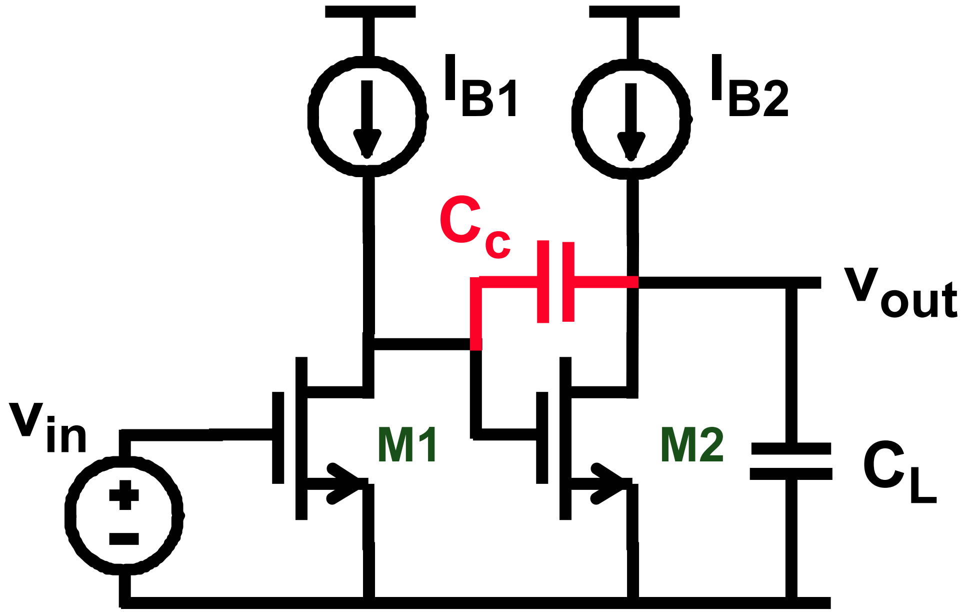
$A_v = (g_m r_{DS})_1 (g_m r_{DS})_2$ $A_v = (g_m r_{DS})_1 (g_m r_{DS})_2$

Cascode versus cascade



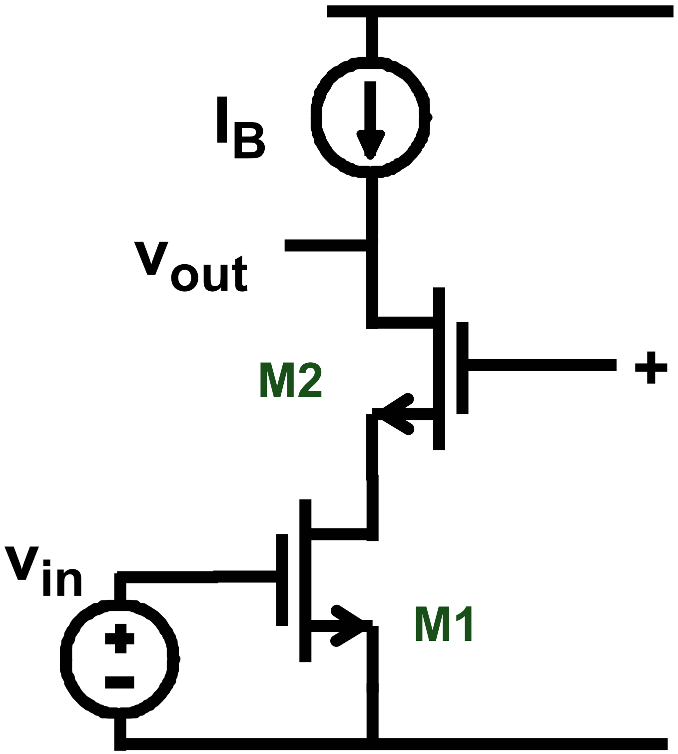
$$GBW = \frac{g_{m1}}{2\pi\, C_L}$$

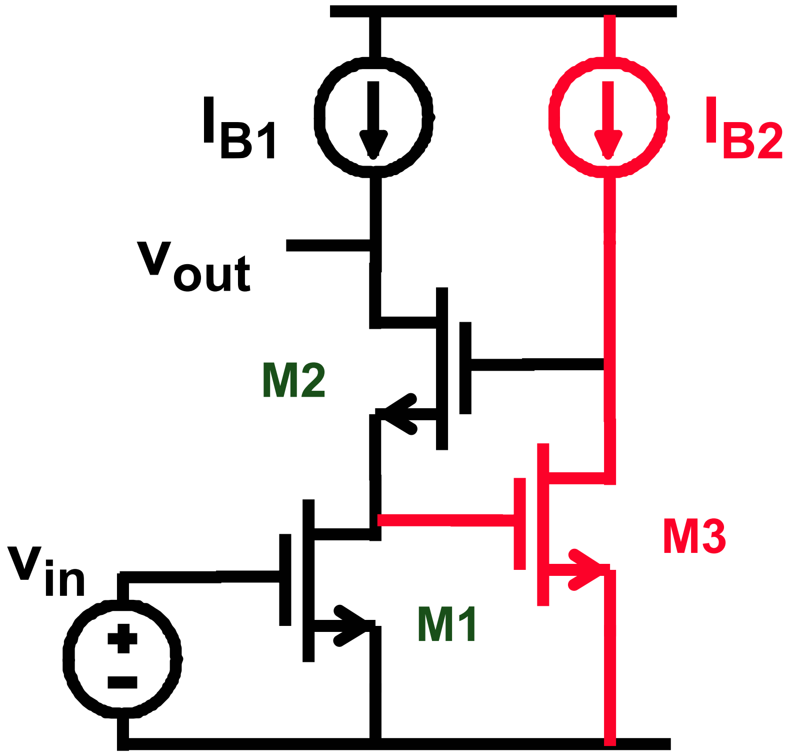
Two-stage Miller amplifier



$$GBW = \frac{g_{m1}}{2\pi\, C_c}$$

Regulated cascode or gain boosting

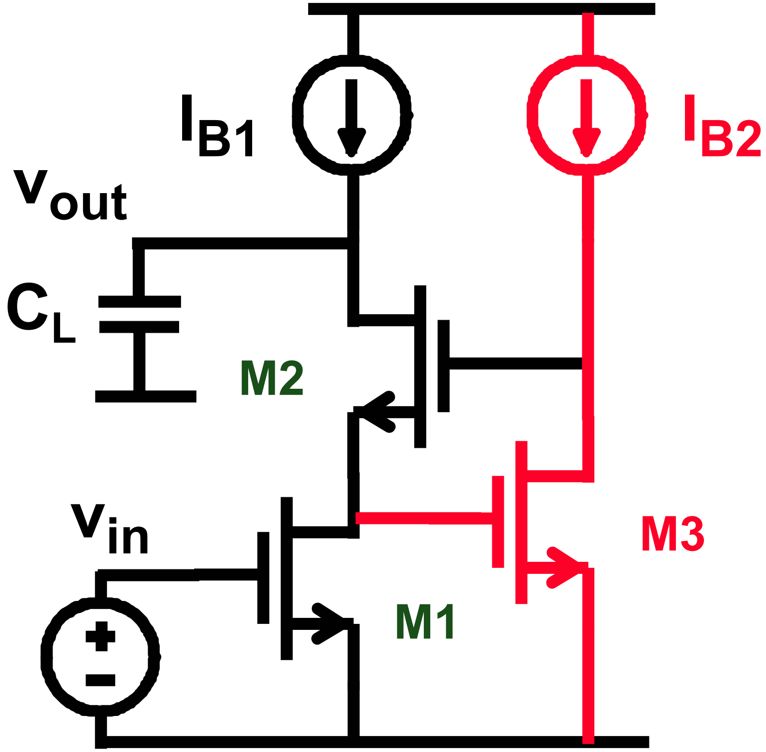


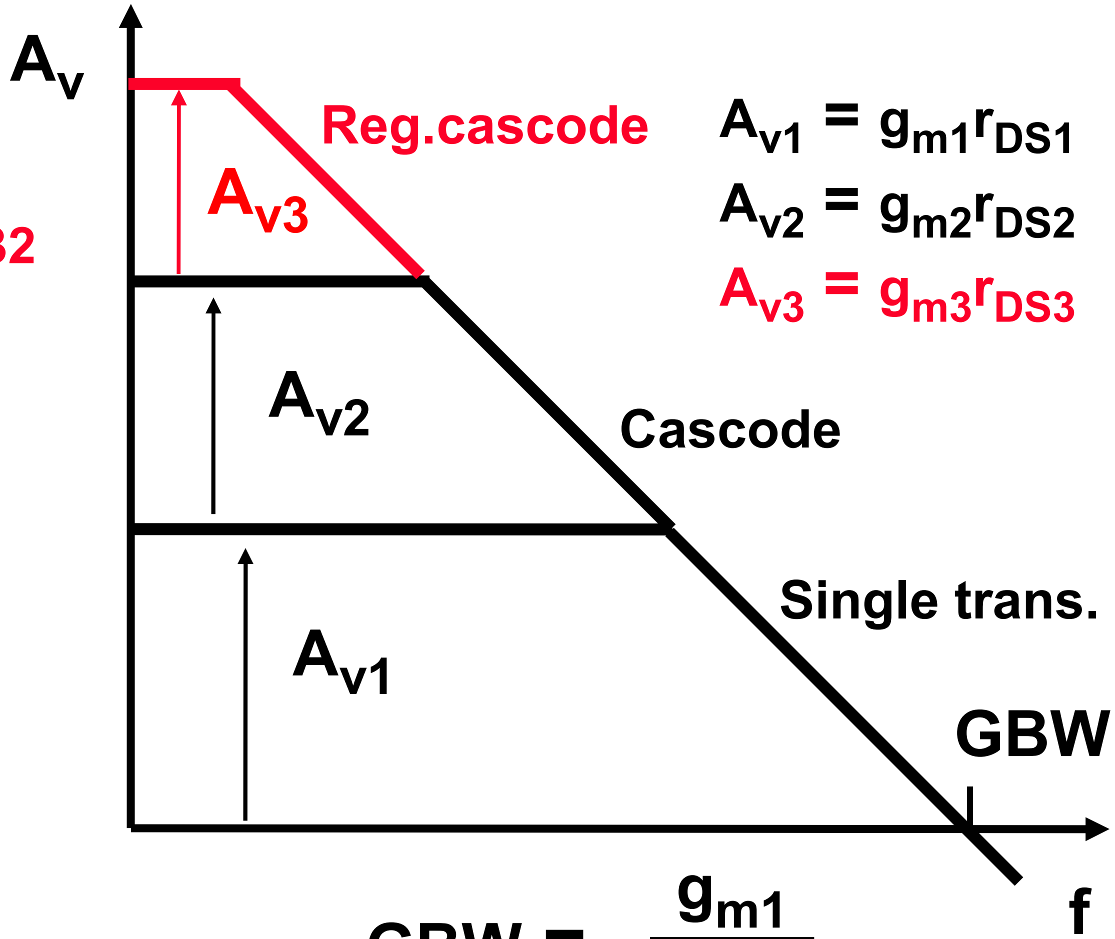


$A_v = (g_m r_{DS})_1 (g_m r_{DS})_2$ $A_v = (g_m r_{DS})_1 (g_m r_{DS})_2 (g_m r_{DS})_3$

Hosticka, JSSC Dec.79, pp. 1111-1114; Sackinger, JSSC Febr.90, pp. 289-298;
Bult JSSC Dec.90, pp. 1379-1384

Regulated cascode, Cascode & single-transistor





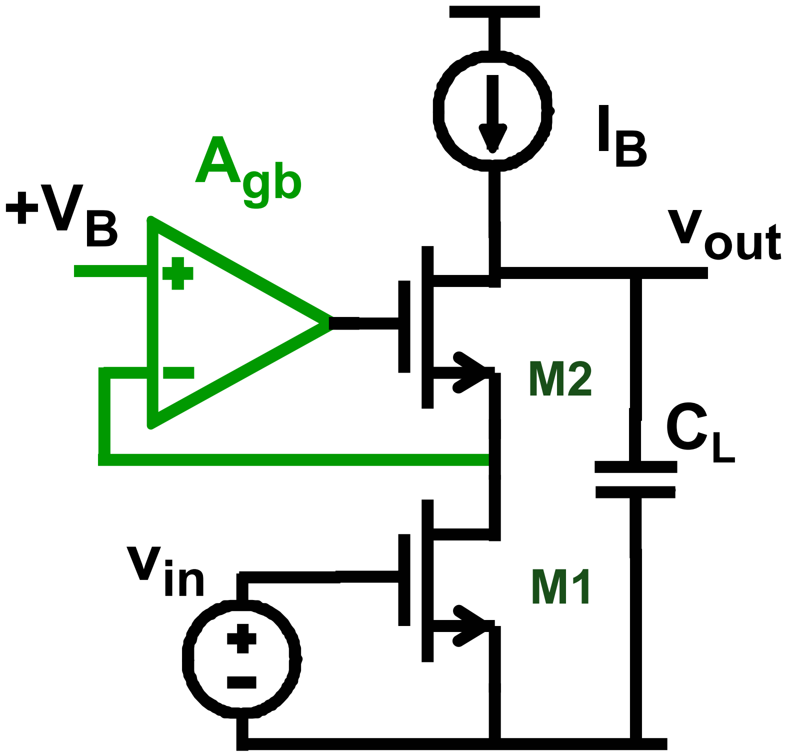
$A_{v1} = g_{m1} r_{DS1}$

$A_{v2} = g_{m2} r_{DS2}$

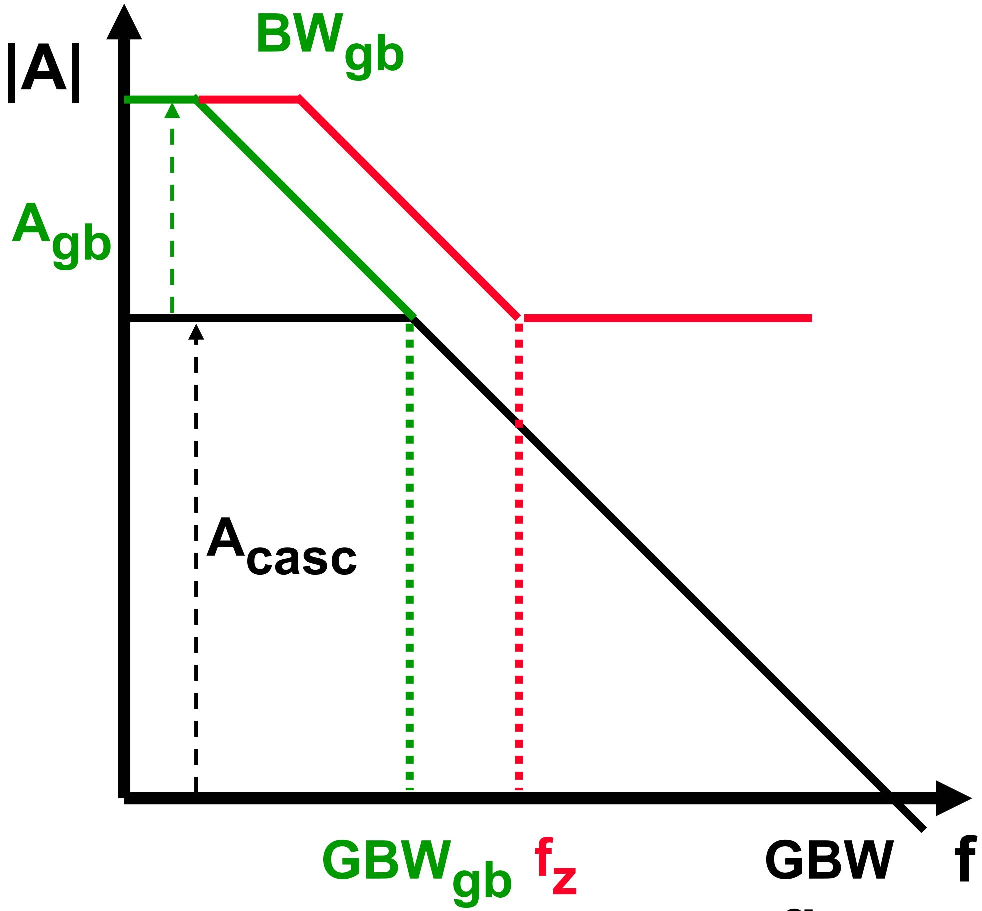
$A_{v3} = g_{m3} r_{DS3}$

$$GBW = \frac{g_{m1}}{2\pi C_L}$$

Gain boosting

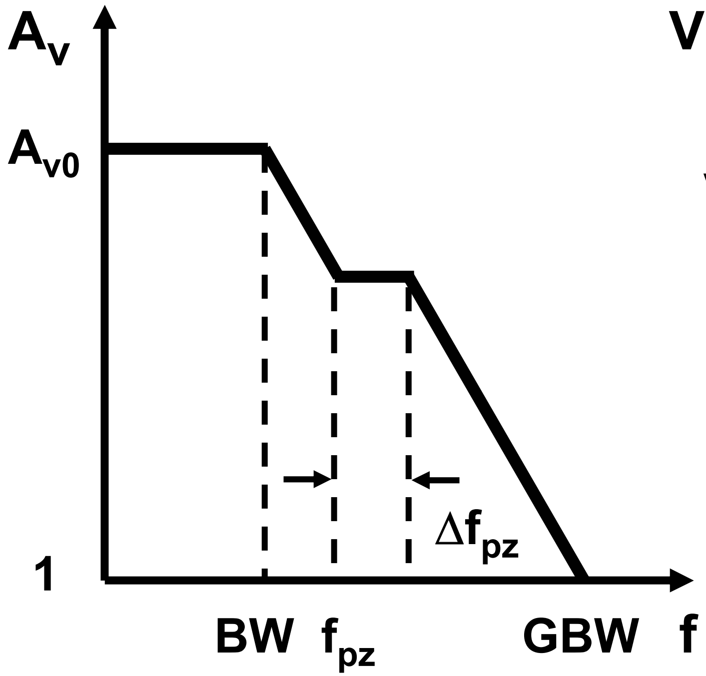


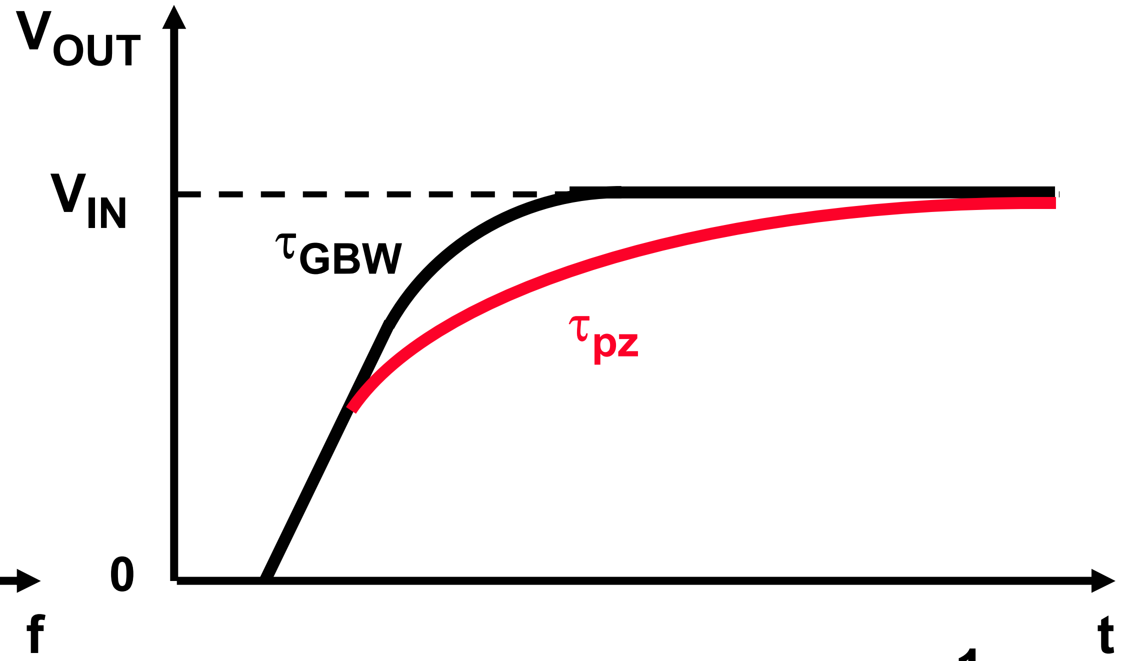
$$A_v = A_{gb}(g_m r_{DS})_1 (g_m r_{DS})_2$$



$$= \frac{g_{m1}}{2\pi\, C_L}$$

Pole-zero doublet and settling time





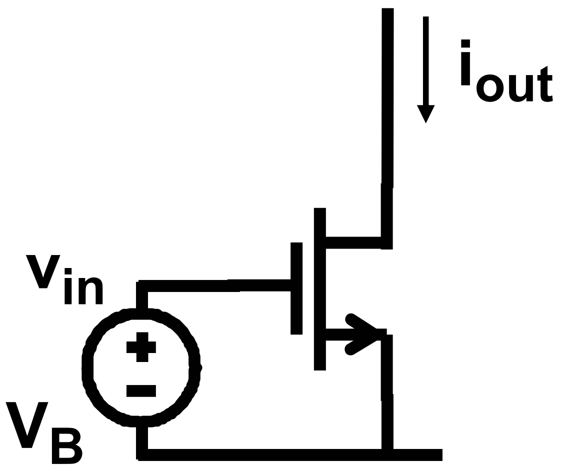
$$f_{pz} = \frac{1}{2\pi\, \tau_{pz}}$$

$$V_{OUT} = V_{IN}\left[1 - \exp\left(-\frac{t}{\tau_{GBW}}\right) - \frac{\Delta f_{pz}}{GBW} \exp\left(-\frac{t}{\tau_{pz}}\right)\right]$$

$$GBW = \frac{1}{2\pi\, \tau_{GBW}}$$

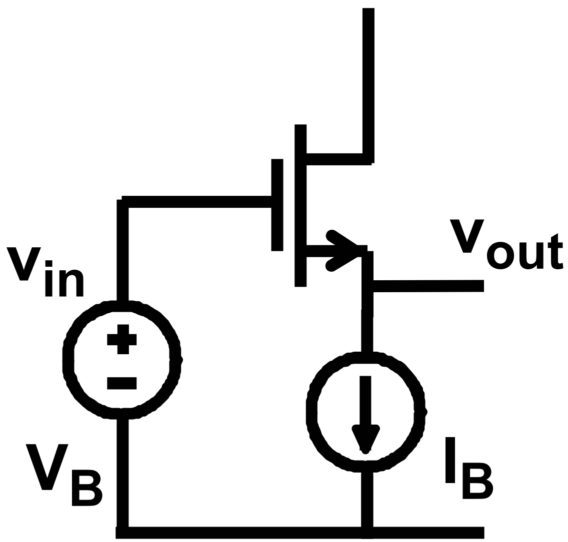
Kamath, etal, JSSC Dec.74, pp. 347-352

Single-transistor stages



$i_{out} = g_m v_{in}$

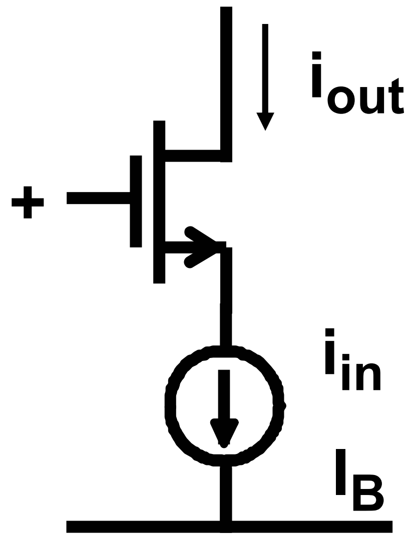
Amplifier



$v_{out} = v_{in}$

$Z_{out} \approx 1/g_m$

Source follower

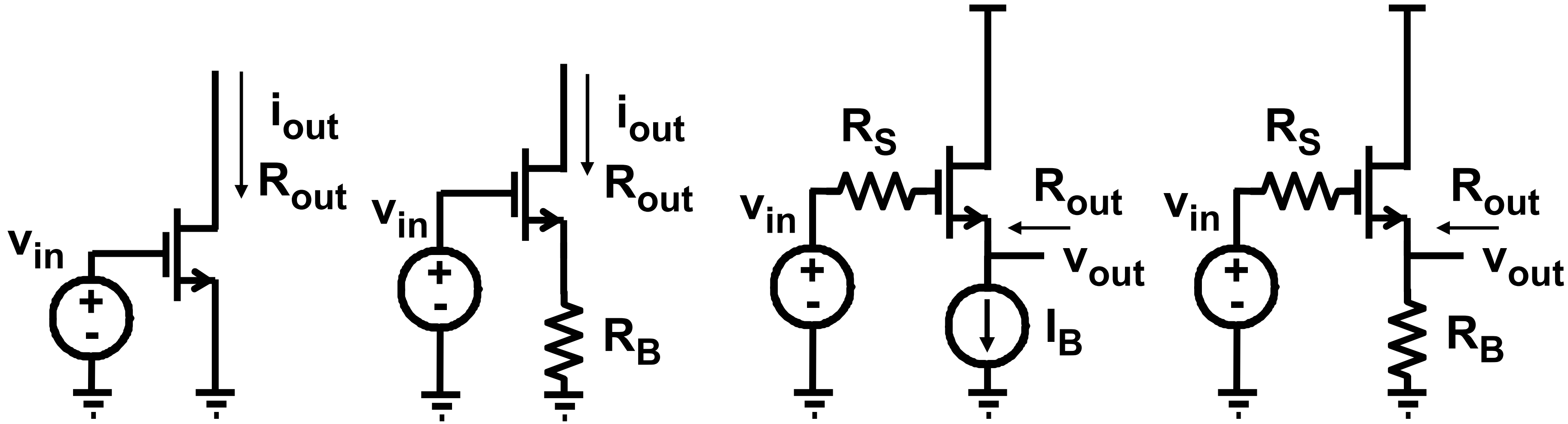


$i_{out} = i_{in}$

$Z_{in} \approx 1/g_m$

Cascode

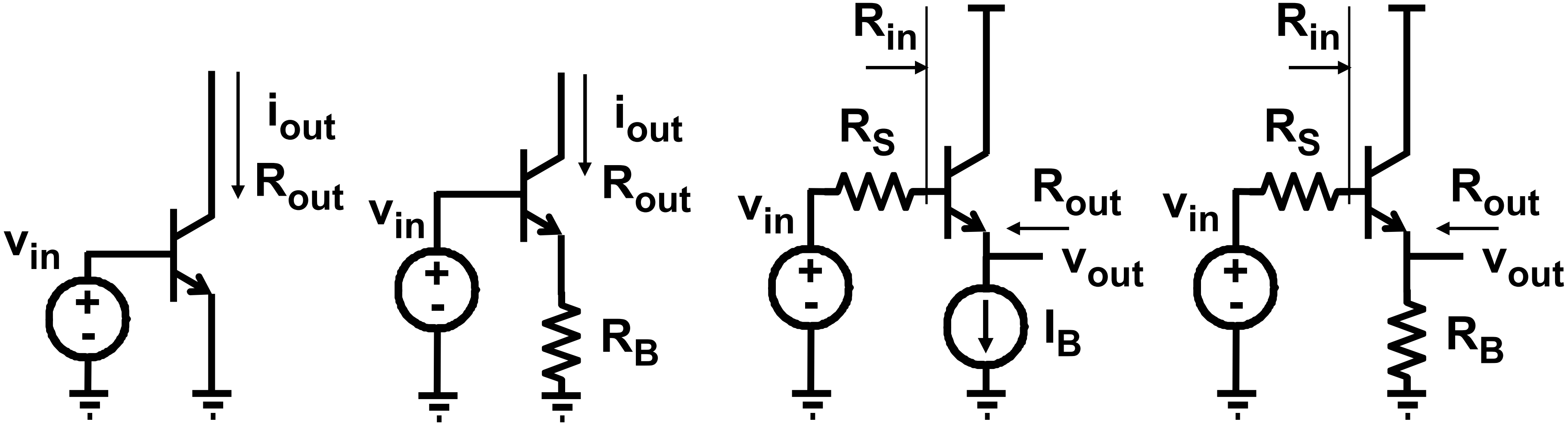
MOST amplifier & follower



$R_B > 1/g_m$ $\qquad\qquad\qquad$ $R_B > 1/g_m$

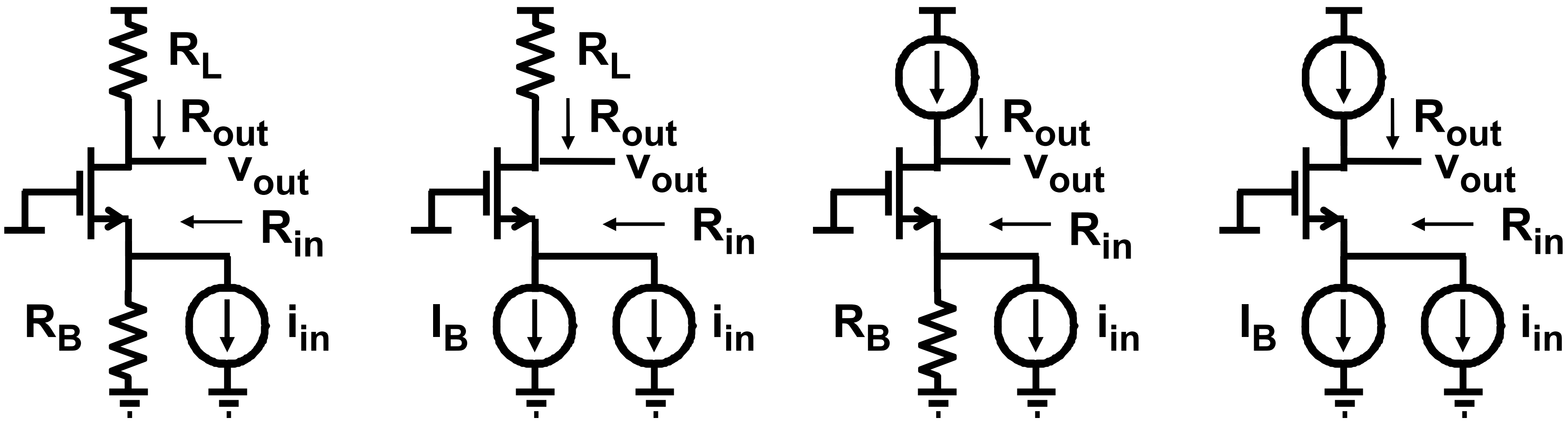
A_G	g_m	$1/R_B$	A_V	1	1
R_{in}	∞	∞		∞	∞
R_{out}	r_o	$g_m R_B r_o$		$1/g_m$	$1/g_m$

Bipolar transistor ($\beta >> 1$)



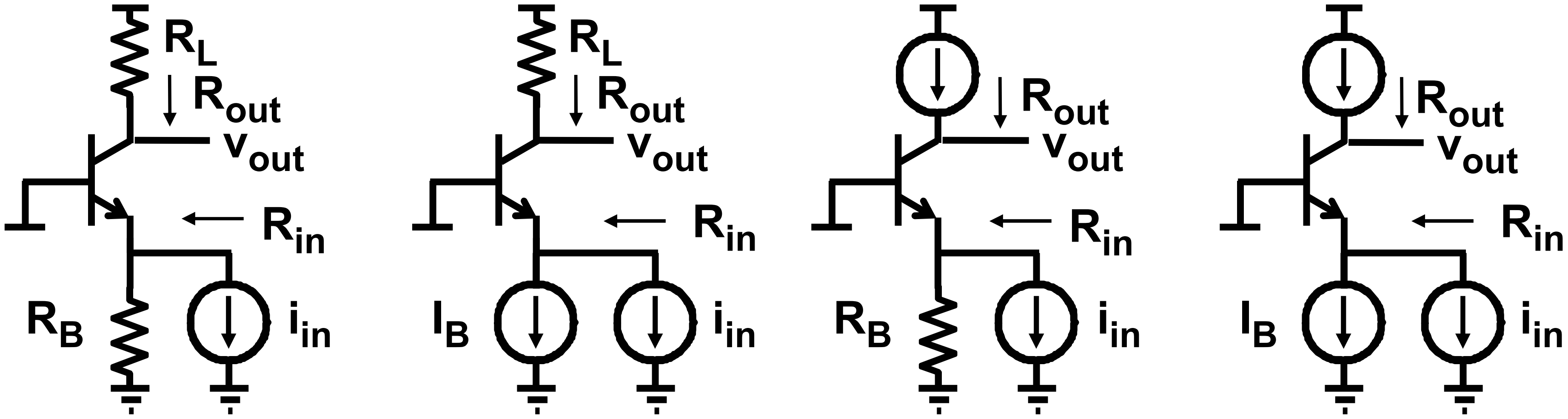
		$R_B > 1/g_m$			$R_B > 1/g_m$
A_G	g_m	$1/R_B$	A_V	1	1
R_{in}	$r_B + r_\pi$	$r_B + r_\pi + \beta R_B$		$r_B + r_\pi + \beta r_o$	$r_B + r_\pi + \beta R_B$
R_{out}	r_o	$g_m R_B r_o$		$1/g_m + R_S/\beta$	$1/g_m + R_S/\beta$

In- & output resistances MOST cascode



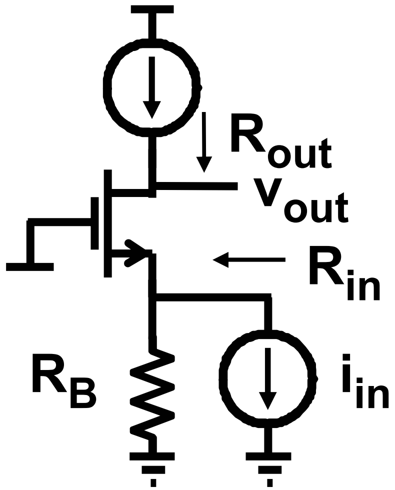
	$R_B > 1/g_m$		$R_B > 1/g_m$	
A_R	R_L	R_L	$g_m r_o R_B$	-
R_{in}	$1/g_m$	$1/g_m$	R_B	∞
R_{out}	$g_m r_o R_B$	∞	$g_m r_o R_B$	∞

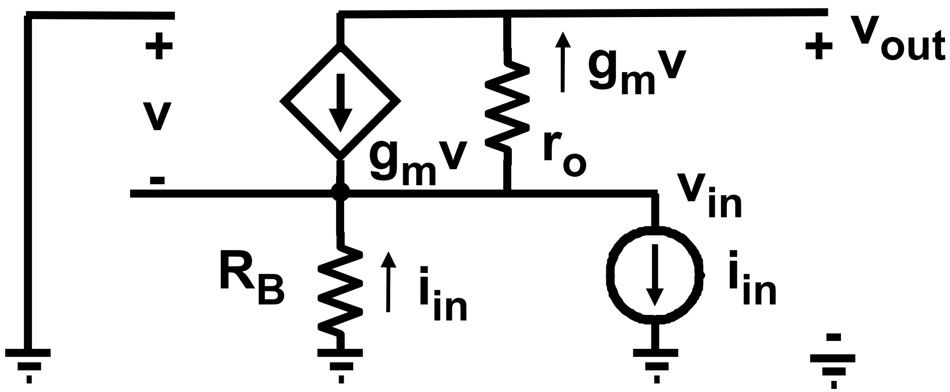
In- & output resistances Bipolar trans. cascode



	$R_B > 1/g_m$		$R_B > 1/g_m$	
A_R	R_L	R_L	$g_m r_o R_B$	-
R_{in}	$1/g_m$	$1/g_m$	$R_B//(r_B+r_\pi)$	r_B+r_π
R_{out}	$g_m r_o R_B$	$\approx \beta r_o$	$g_m r_o(R_B //(r_B+r_\pi))$	$\approx \beta r_o$

Calculation of A_R for a MOST cascode





$R_B > 1/g_m$

$$A_R = g_m r_o R_B$$

$$\begin{cases} v = - v_{in} \\ v_{out} = v_{in} - g_m v\, r_o \\ v_{in} = - R_B\, v_{in} \end{cases}$$

yields $v_{out} = - R_B\, i_{in} (1 + g_m r_o)$

and $g_m r_o >> 1$

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