5 March 2020

وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا

10 رجب 1441

Analog IC Design

Lecture 06
Basic Amplifier Stages

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Outline

- Recapping previous key results
- Why amplifiers?
- Basic amplifier operation
- Basic amplifier analysis
- Rin/out shortcuts
  - Looking from drain
  - Looking from source
- GmRout method
- Basic amplifier topologies
  - Common Source (CS)
  - Common Gate (CG)
  - Common Drain (CD) – Source Follower (SF)
- Large signal behavior

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MOSFET in Saturation

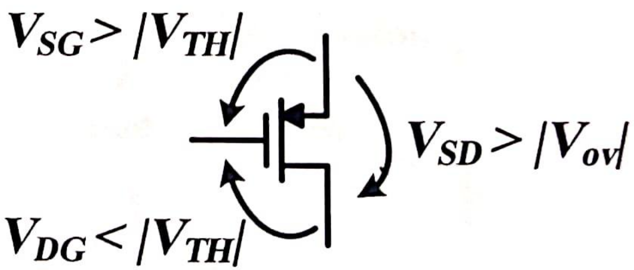
- The channel is pinched off if the difference between the gate and drain voltages is not sufficient to create an inversion layer

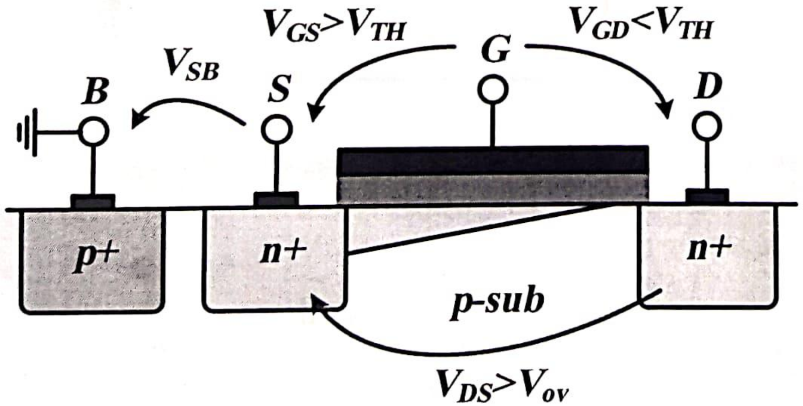
  $V_{GD} \leq V_{TH} \quad OR \quad V_{DS} \geq V_{ov}$

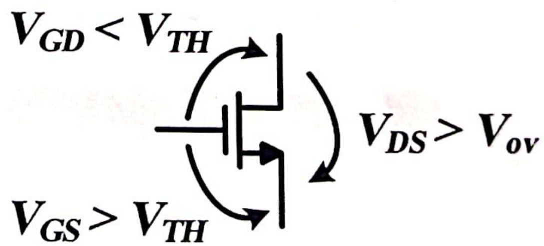
- Square-law (long channel MOS)

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

$$V_{SB} \uparrow \; \Rightarrow \; V_{TH} \uparrow$$







Regions of Operation Summary

OFF (Subthreshold)

$V_{GS} < V_{TH}$

ON

$V_{GS} > V_{TH}$

Triode

$V_{DS} < V_{ov}$

Or

$V_{GD} > V_{TH}$

$$I_D = \mu C_{ox}\frac{W}{L}\left(V_{ov}V_{DS} - \frac{V_{DS}^2}{2}\right)$$

Pinch-Off (Saturation)

$V_{DS} \geq V_{ov}$

Or

$V_{GD} \leq V_{TH}$

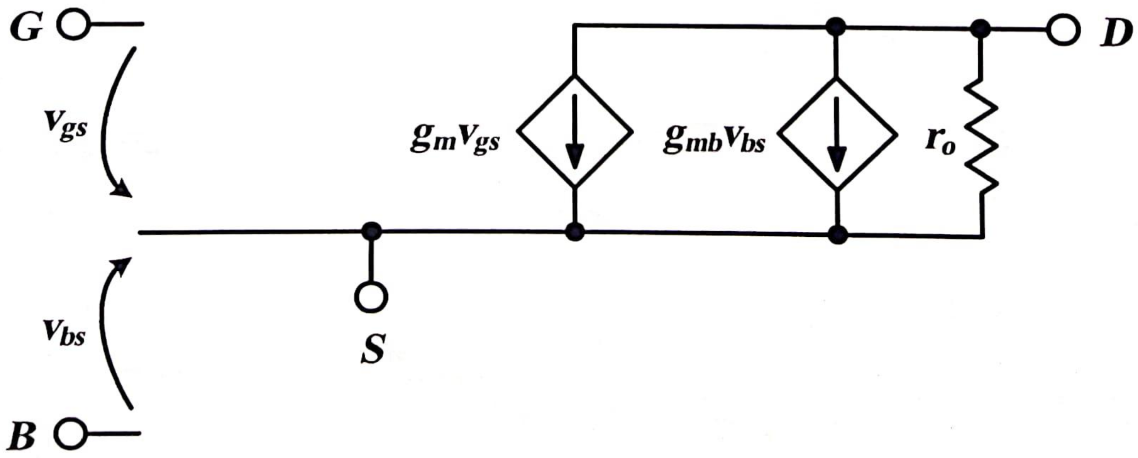
$$I_D = \frac{\mu C_{ox}}{2}\frac{W}{L}V_{ov}^2(1 + \lambda V_{DS})$$

Low-Frequency Small-Signal Model

$$g_m = \frac{\partial I_D}{\partial V_{GS}} = \mu C_{ox}\frac{W}{L}V_{ov} = \sqrt{\mu C_{ox}\frac{W}{L}\cdot 2I_D} = \frac{2I_D}{V_{ov}}$$

$$g_{mb} = \eta g_m \qquad \eta \approx 0.1 - 0.25$$

$$r_o = \frac{1}{\partial I_D/\partial V_{DS}} = \frac{V_A}{I_D} = \frac{1}{\lambda I_D} \qquad V_A \propto L \leftrightarrow \lambda \propto \frac{1}{L} \qquad V_{DS}\uparrow V_A \uparrow$$



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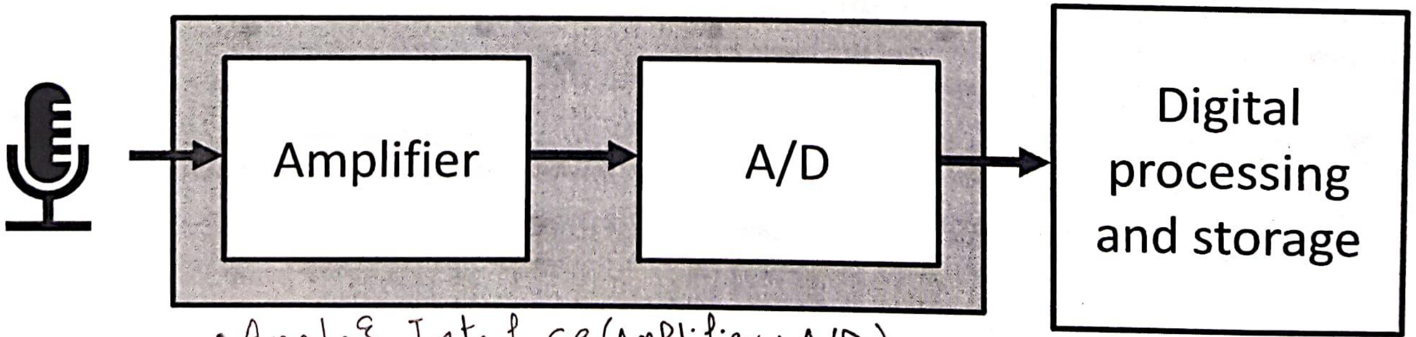
Why Amplifiers?

- All the physical signals in the world around us are analog
  - Voice, light, temperature, pressure, etc. (wireless signals, electromagnetic waves)
- We (will) always need an "analog" interface circuit to connect between our physical world and our digital electronics
- The physical signals are usually very weak
  - They must be amplified before any kind of processing

*Why Amplifiers? → also it's used in Power management not only interfaces

- Amplifiers are also needed in many other applications

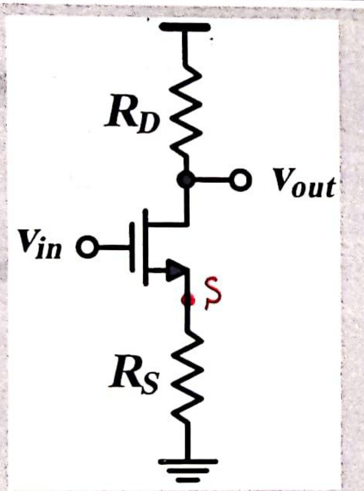
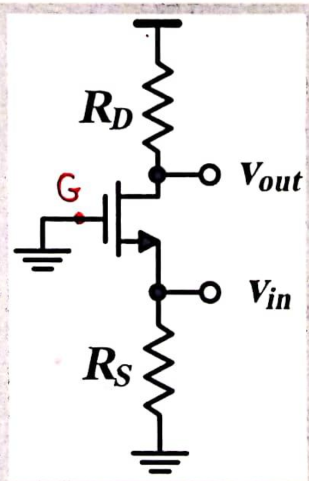
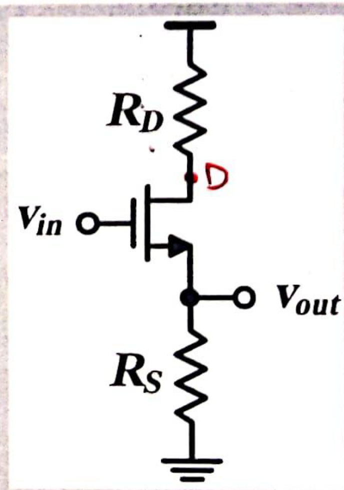


• Analog Interface (Amplifier + A/D)

*On the other hand: when we learn how to design amplifiers we will learn all the important concepts in analog design (small signal model, frequency response, stability, feedback, etc.) many concepts we will learn in the context of the amplifiers but we will benefit from them while designing any analog block.

Basic MOSFET Amplifier Topologies

• Common between i/P & o/P

	Common Source (CS)	Common Gate (CG)	Common Drain (CD) Source Follower (SF)
			
	Voltage & current amplifier	Voltage amplifier Current buffer	Voltage buffer Current amplifier
In	*G*	*S*	*G*
Out	*D*	*D*	*S*

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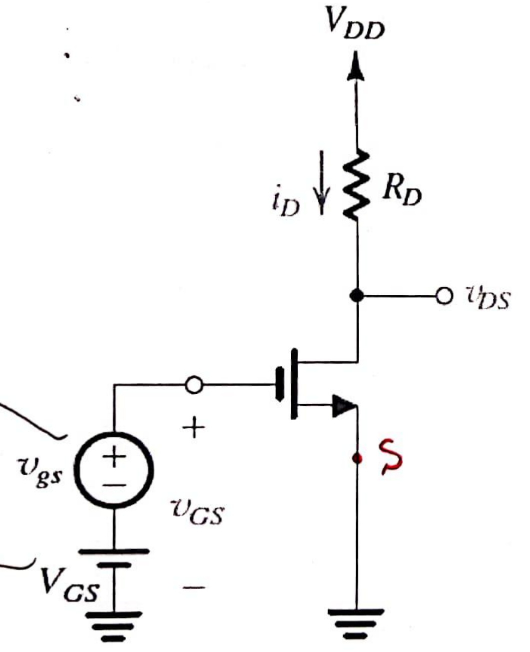
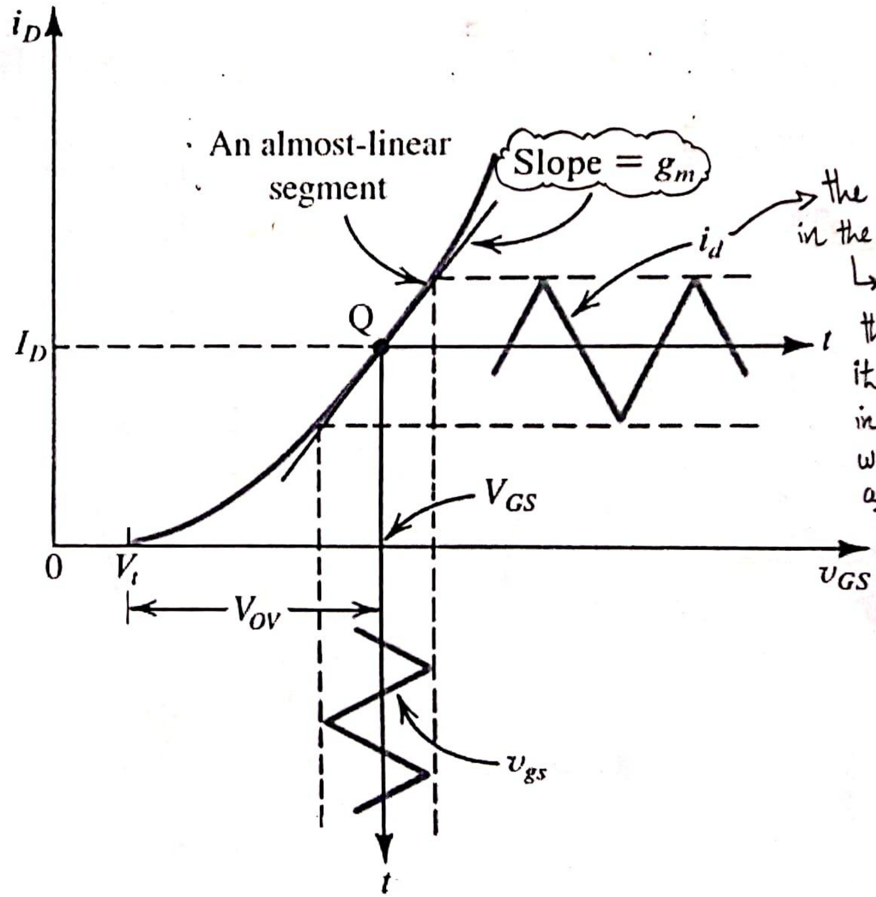
CS Amplifier Example

"small signal"
small perturbation
ΔV_{GS}

DC Bias
Q pt



'Common Source'
Amplifier



the result perturbation in the current
↳ after flowing through the resistance "R_D" it will results a perturbation in the o/p voltage V_{DS} which can be described as a amplified version of the i/p signal.
(V_{DS})

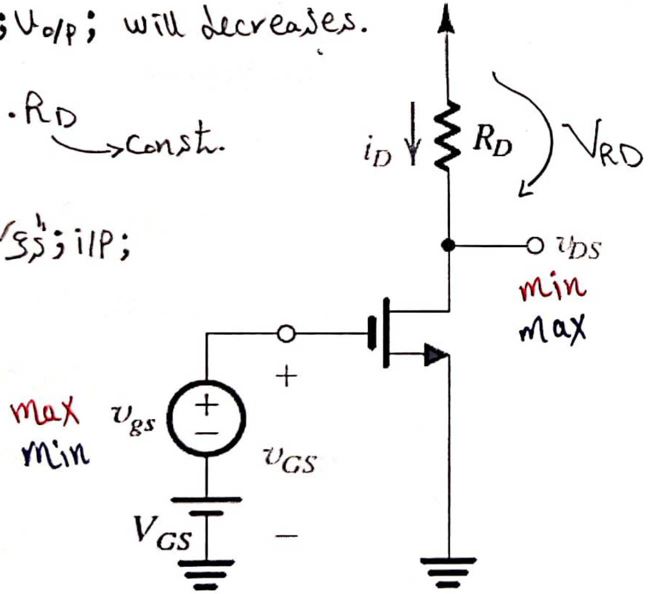
[Sedra/Smith, 2015]

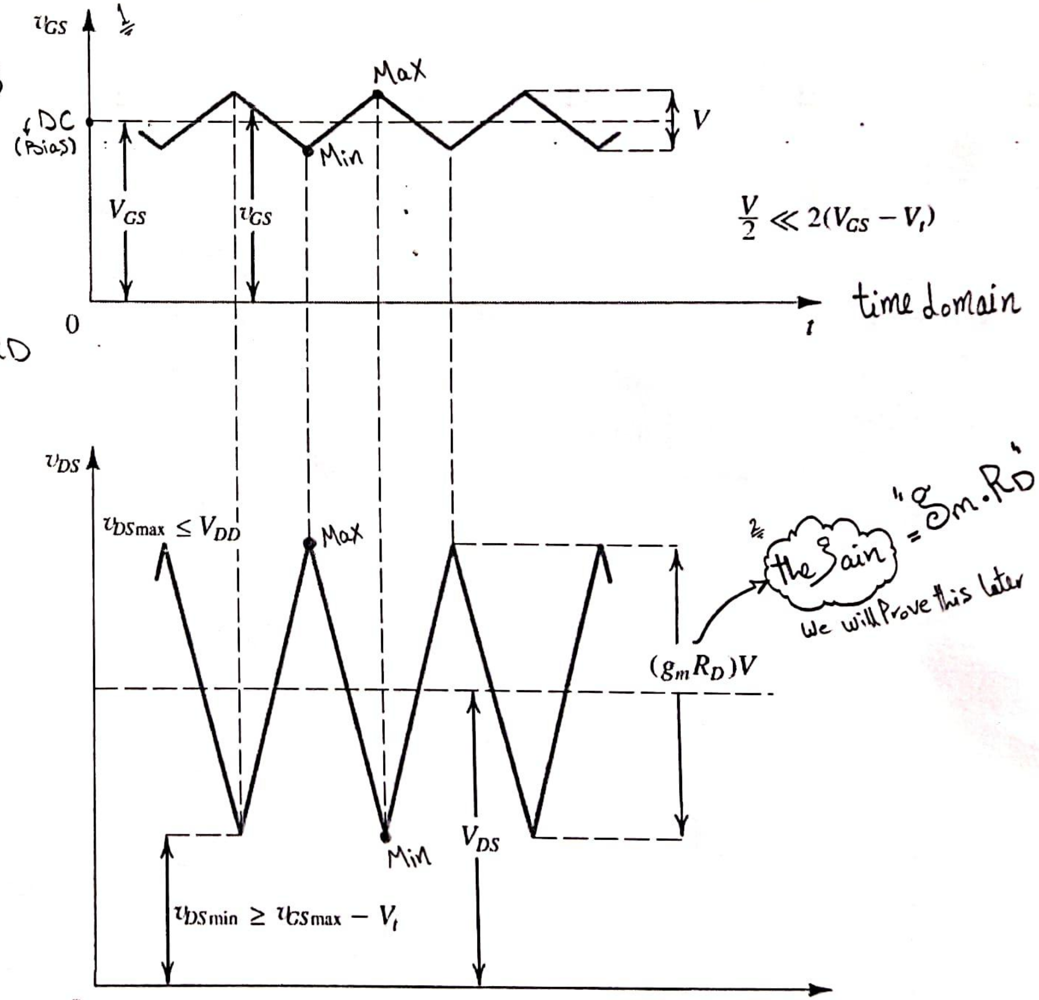
CS Amplifier Example

★ There is a "180°-Phase shift" between the o/P & i/P, Why?
By increasing $v_{gs}\uparrow$ then $i_D\uparrow$ will increasing making the voltage drop on $R_D\uparrow$ which will results that the voltage v_{DS}; $V_{o/p}$; will decreases.

$v_{DS} = V_{DD} - i_D \cdot R_D$

v_{DS} → o/P; V_{DD} → Const.; R_D → Const.; i_D → $\propto$ "v_{gs}"; i/P;





[Sedra/Smith, 2015]

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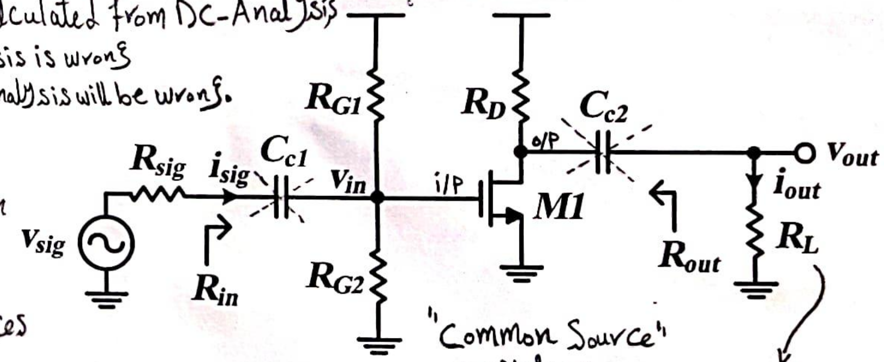
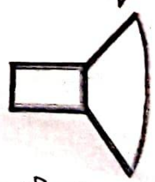
Amplifier Analysis Steps

1. DC analysis
   - Coupling and bypass capacitors → open-circuit (o.c) ★ $X_c = \frac{1}{wc}$, for DC → $w = 0$ ∴ $X_c = \frac{1}{0} = \infty$
   - Calculate Q-point and check operation in saturation ($V_{DS} > V_{ov}$)
2. Calculate small signal parameters (g_m, r_o) — f (I_D): calculated from DC-Analysis
   • If DC Analysis is wrong ∴ The whole analysis will be wrong.
3. Draw the small signal equivalent circuit
   - DC voltage source → short-circuit (s.c.) } Deactivation for all DC Sources
   - DC current source → open-circuit (o.c.) }

   Independant Sources
   - Coupling and bypass capacitors → short-circuit (s.c) (until frequency response) → Assume high frequency ∴ $X_c = \frac{1}{\omega_c \uparrow\uparrow}$
4. Determine the amplifier parameters (4 Parameters)
   - Input resistance and output resistance
   - Voltage gain and current gain



"Common Source" Amplifier



ex.: Speaker

3.9: After applying the small signal model, you will have linear circuit, the non-linear part was in the DC-analysis (square law)

3.1 ★ We don't amplify the battery; we amplify a small signal which is on the input port of the amplifier (ex. signal from a microphone) we give it power to be amplified and come from the output port, this power comes from the battery.

Amplifier Parameters

1- R_{in} : is the resistance you will see when you look from the input port

2- R_{out} : is like Norton or Thevenin resistance, we first deactivate all the independent sources (only one 'v_{sig}'), but where is the dependent source? - MOSFET, then imagine you put a voltage source 'V_x' @ o/P Port this voltage source will generates current i_x → $R_{out} = \frac{V_x}{i_x}$

1.2

- ☐ $R_{in} = \dfrac{v_{in}}{i_{in}} = \dfrac{v_{in}}{i_{sig}}$ Ohm's Law

independent source

- ☐ $R_{out} = \dfrac{v_x}{i_x}$ @ $v_{sig} = 0$

Voltage divider between 'R_{in}' & 'R_{sig}'

the voltage direct to the MOSFET (gate)

usually a known forms

3/4

- ■ $Voltage\ gain = A_v = \dfrac{v_{out}}{v_{sig}} = \dfrac{v_{in}}{v_{sig}} \cdot \dfrac{v_{out}}{v_{in}} = \dfrac{R_{in}}{R_{sig}+R_{in}} \cdot \dfrac{v_{out}}{v_{in}}$ ⟹ Must be done on two steps "Divide & Conquer"

• The most important Parameter

• The signal we want to amplify

→ ohm's law

3.5 You tell us before that the input resistance of the MOSFET is infinity, don't you? - yes but it depends on the circuit
• in this circuit it's not infinity (as I told you) it is $R_{G1} // R_{G2}$.
★ Actually what differ from one amplifier to another is R_{in} equation. But the voltage divider doesn't change.

- ☐ $Current\ gain = A_i = \dfrac{i_{out}}{i_{sig}} = \dfrac{v_{out}/R_L}{v_{in}/R_{in}} = \dfrac{v_{out}}{v_{in}} \cdot \dfrac{R_{in}}{R_L}$

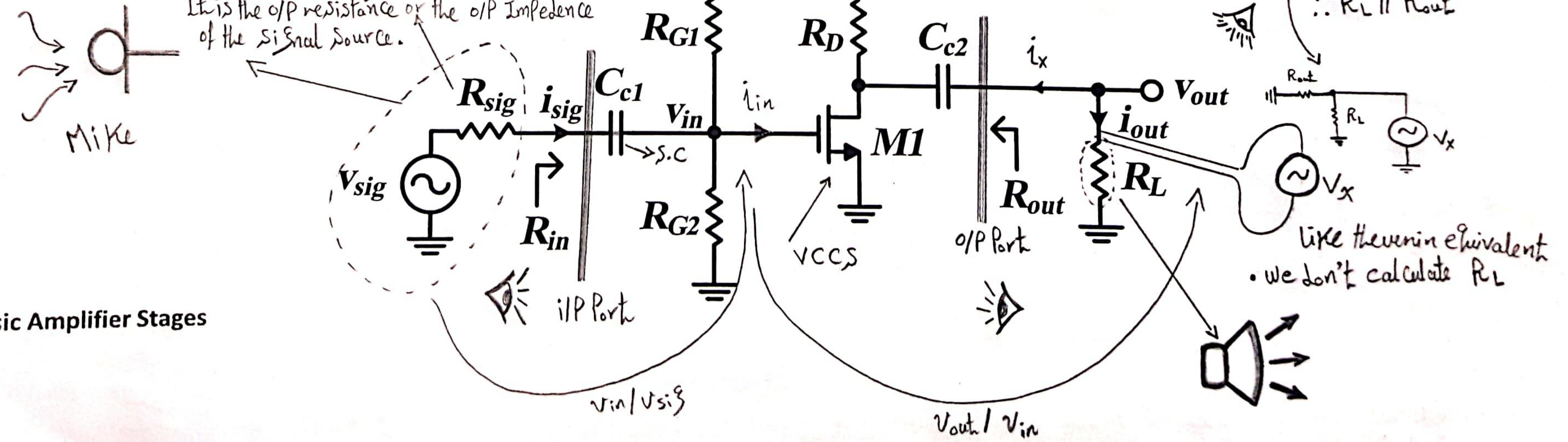
reuse

4- i_{out} : is the current flowing through the load (in this ex.) the load can be the speaker which exports the sound we want to amplify

$i_{sig} = i_{in}$

1.1 ★ This resistance R_{sig} doesn't belong to the Amplifier but, It is the o/P resistance or the o/P Impedence of the signal source.

2.5 • Sometime we want to calculate all the resistances connected to the o/P
∴ $R_L // R_{out}$



Large and Small Signal Analysis

	Large Signal Analysis	Small Signal Analysis
Model	Large signal model	Small signal model
Linearity	Non-linear (Square law)	Linear
Simulation	transient analysis is very slow as the circuit is non linear. DC and transient analysis ↳ Simulation with time	circuit response with frequency. AC analysis • If you used the simulator before you have probably noticed that the AC analysis is very fast → As your circuit is linear
Purpose	Calculate bias point, signal swing, distortion, etc. or Slew rate — transient	Calculate $A_v, R_{in}, R_{out}, BW, etc.$
VDC	✓	s.c.
IDC	✓	o.c.
Capacitor	o.c. (in DC) $i = C\frac{dV}{dt}$ (in transient)	$1/\omega C$
Inductor	s.c. (in DC) $V = L\frac{di}{dt}$ (in transient)	ωL

DC Sources

Deactivation

• AC is very fast (linear)
• Transient is very slow
↳ non linear circuit
solved by:
"Numerical Iterations"

will be taken into consideration → 'frequency Response'

• Differential equations are also reason to decrease the speed of the transient analysis.

★ Why Cap. & Ind. are O.C. & S.C in DC but have value in Transient? - as DC is Const. Voltage then $\frac{dV}{dt} = 0$, but transient in variable voltage ↳ so, we can't neglect them.

ramp

sin

Amplifier Analysis Example

1 ★Assume biased in saturation unless otherwise stated.
• But this don't underestimate the importance of biasing.
if the Biasing is not Correct every thing will be wrong.
↳ also in the Simulation first thing to debug is the Bias Point.

1.7 we wanna calculate the voltage gain.

$$v_{out} = -(g_m v_{in}) r_o \quad , V_{in} = V_{gs}$$

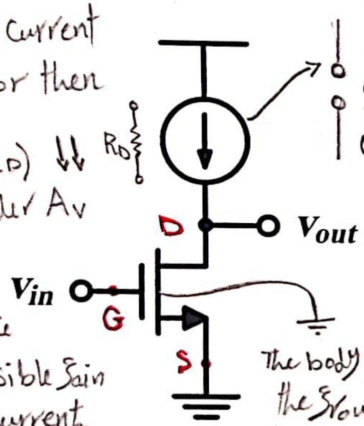
2.1 $$|A_v| = \left|\frac{v_{out}}{v_{in}}\right| = g_m r_o$$

3 ★ $g_m . r_o$ "intrinsic gain"
one of the important Parameters used when designing Analog circuits.
it is one of the "figures of merit".
• figures of merit: numerical expression representing the Performance or efficiency of a given device, material or Procedure.

3.1 ❑ $g_m r_o$ is the max gain that can be obtained from a single transistor: a.k.a. intrinsic gain

in a Common Source amplifier

4 ★Practically: the gain will be less than the intrinsic gain
↳ If we replace the current Source with a resistor then
$V_{out} = -(g_m V_{in}).(r_o // R_D)$ ↓↓
which will results smaller A_v
★
∴ the ideal load in analog design is to use current Source
a) it Provides the max. Possible gain
b) Providing the needed current without reducing the resistance
∴ without reducing the gain.

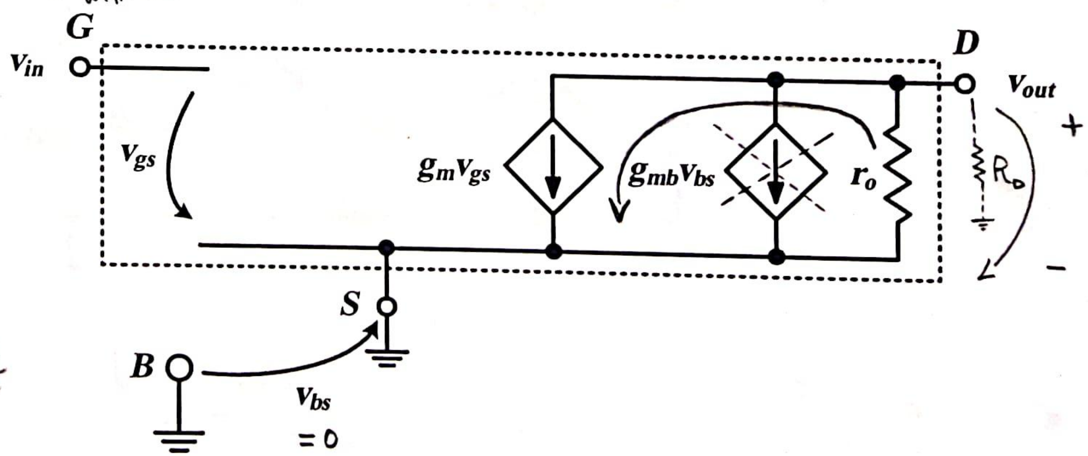


1.6 DC current Source (Bias)

The body is connected to the ground by default (as it is not drawn)

• very simple CS Amplifier

1.5 connect every terminal in the box with that connected to it in the circuit.



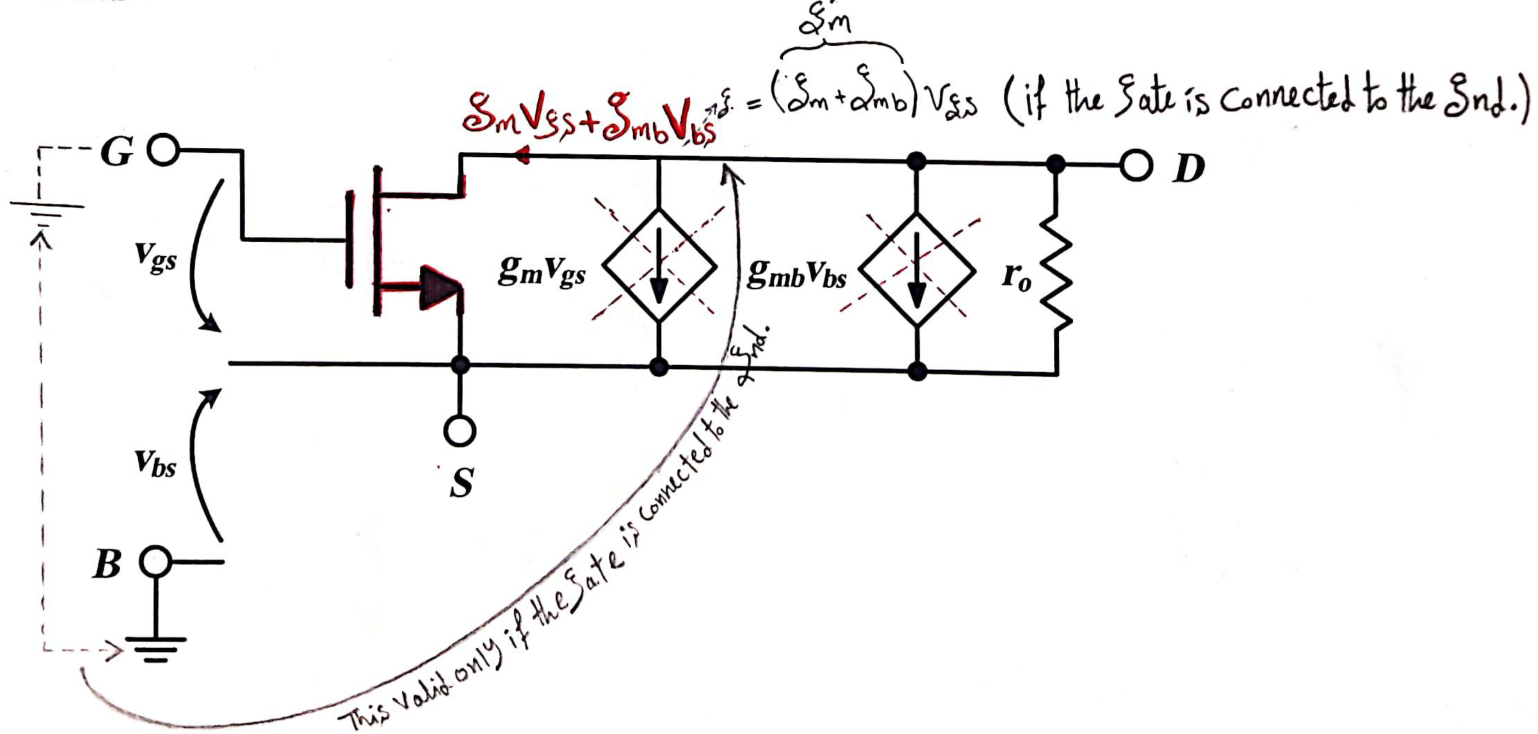
2 opposite to the direction of the current so, $-(g_m V_{in}) r_o$ "−ve sign"

Direct Analysis on Schematics

★ one of the most important things you need to learn is the direct analysis on the schematics as if you have a circuit with 10 or 20 transistor it will be hard but impossible to replace each transistor and draw the model as it will take much time and you will probably go wrong

★ So, you should do the analysis direct on the schematic without drawing the equivalent circuit.

- No need to draw the small signal model every time
- Just remember we have two VCCSs and r_o between D and S
- If G is ac gnd, then $v_{bs} = v_{gs}$ ➔ g_m and g_{mb} add
  - $g_m \rightarrow g_m + g_{mb}$



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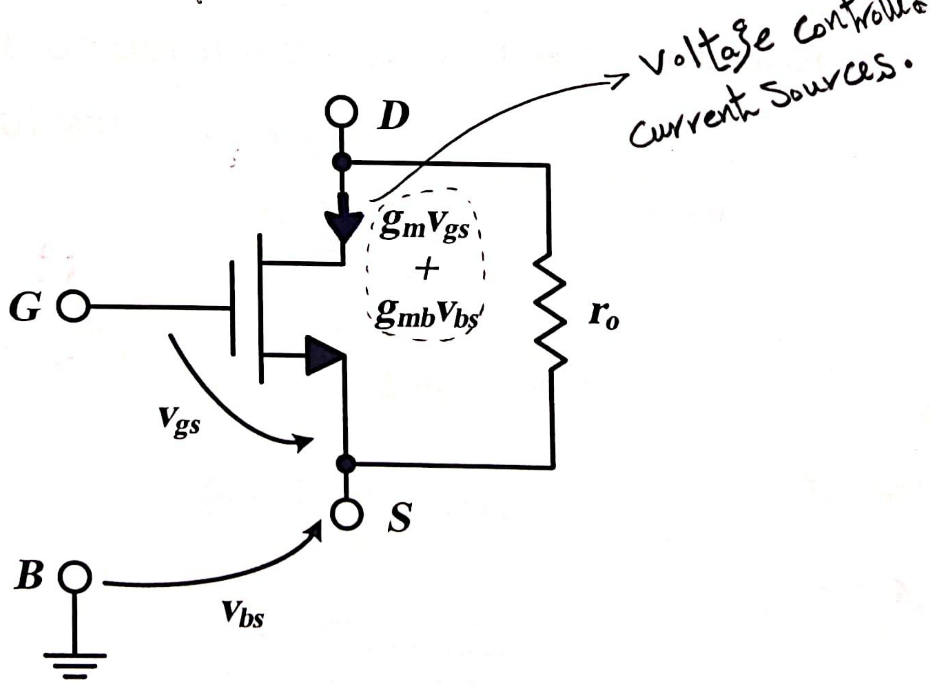


Intrinsic Gain

$$v_{out} = -(g_m v_{in}) r_o$$

$$|A_v| = \left|\frac{v_{out}}{v_{in}}\right| = g_m r_o$$

② ★ In the past technologies
$g_m r_o > 100$
> 50
so, these approximations where valid
→ from the cons of the scaling down is that:
$g_m r_o < 10$ (intrinsic gain decreases)
which makes some issues we will study later in the course

- ❑ $g_m r_o$ is the max gain that can be obtained from a single transistor
- ❑ Common approximations that we usually use

$$g_m r_o \gg 1$$

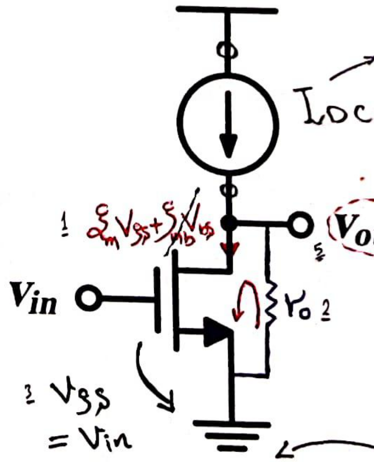
★ The most important approximation we use in analog design.

① ex. ★ $\frac{1}{g_m} = 100K\Omega$
→ how we considered this as a low value?
• As it is a relative value you should compare it to r_o in the same circuit.
$r_o = 10M\Omega$
$\therefore 10M\Omega >> 100K\Omega$

"high impedance" $r_o \gg \frac{1}{g_m}$ "low" impedance

$$g_m + \frac{1}{r_o} \approx g_m$$

$$r_o // \frac{1}{g_m} \approx \frac{1}{g_m}$$



Don't forget $I_{DC} = 0$

$g_m V_{gs} + g_{mb} V_{bs}$

$V_{out} = (-g_m V_{gs}) * r_o$

$V_{gs} = V_{in}$

$V_{DS} = 0$

B

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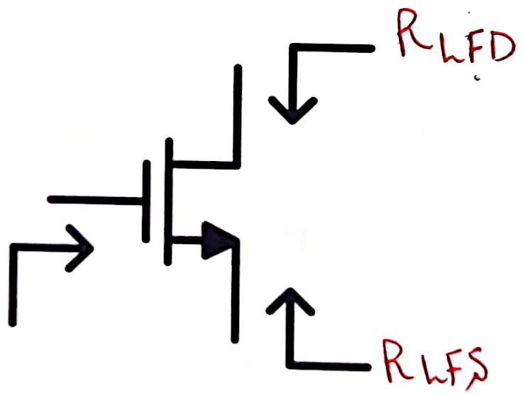
Rin/out Shortcuts

- Find equivalent impedance looking from Gate, Source, and Drain



• The Gate is a capacitance

$\frac{1}{wC}$ ∞

@low frequencies = ∞

★ For BJT:

• You have to calculate $R_{\text{Looking from Base}}$

- as the base isn't open circuit.

Looking From Drain

- If G is ac gnd, then $v_{bs} = v_{gs}$ ➔ g_m and g_{mb} add
- $v_{gs} = -i_x R_S$ and $g_m r_o \gg 1$
- 4 Apply KCL at D

$i_{in} = i_{out}$ @ D i₂ "ohm's law"

$$i_x = (g_m + g_{mb})\underbrace{(-i_x R_S)}_{i_1 \,(V_{GS})} + \frac{v_x - i_x R_S}{r_o}$$

4.5 ★ If we put everything in terms of V_x and i_x then the problem is solved.

5 $$R_{LFD} = \frac{v_x}{i_x} = r_o + [(g_m + g_{mb})r_o + 1]R_S \approx r_o[1 + (g_m + g_{mb})R_S]$$

as: $g_m r_o \gg 1$

we can't neglect g_{mb} as the source is floating not connected to the ground. ($V_{BS} \neq 0$)

1.5 ★ It's useful to solve as many unknowns as possible on the schematic without writing too many equations.

• reduce unknown $V_a = i_x \cdot R_S$

It will help where the o/p current @ a = i_x

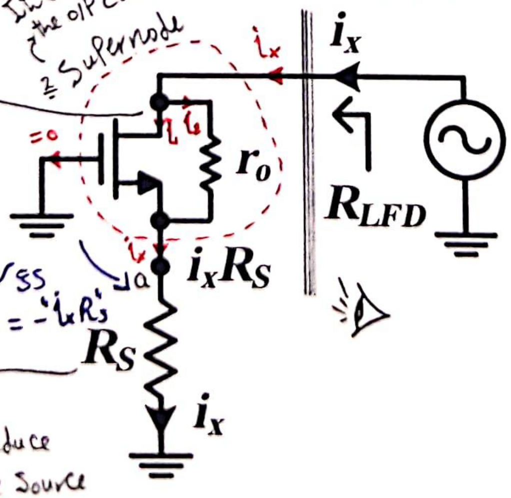
2 supernode

4 $i_1 = (g_m + g_{mb})V_{GS}$

=0

1 $V_{GS} = V_{BS}$ as gate to ground

3 $V_{GS} = V_G - V_S = 0 - i_x R_S = -i_x R_S$



1.75 ★ $R_{LFD} = \frac{V_x}{I_x}$

6 • we put R_S to deduce the general case, but if the source is to ground then put $R_S = 0$ → special case

Looking From Drain

$$\boxed{R_{LFD} \approx r_o[1 + (g_m + g_{mb})R_S]}$$

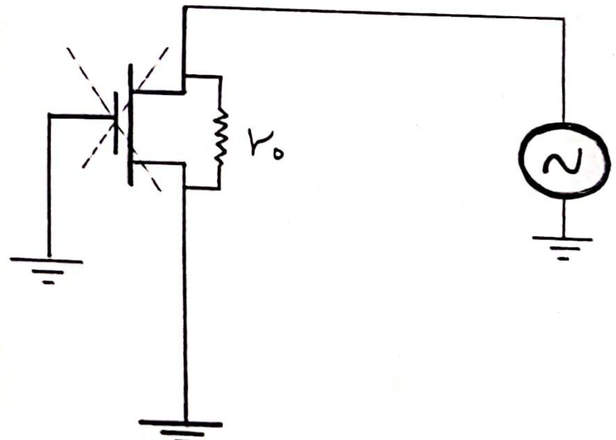
★ $g_m r_o >> 1$

- Special case: $R_S = 0$ (G and S ac s.c.) ➔ **active load**

$$\boxed{R_{LFD} = r_o}$$

Active Load

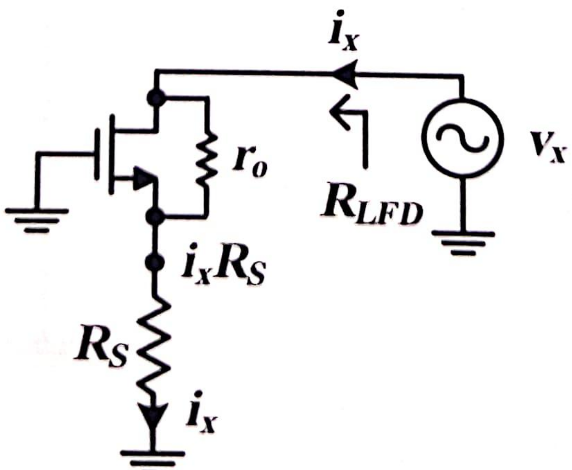
↳ Gate & Source are "AC S.C."



- **Drain is a high-impedance node (H.I.N.)**

↳ as if R_S has a value ∴ $R_{LFD} > r_o$

∴ R_{LFD} will be very high-impedance.



★ Why we called it active source?

- when $R_S = 0$

∴ $V_{GS} = 0$

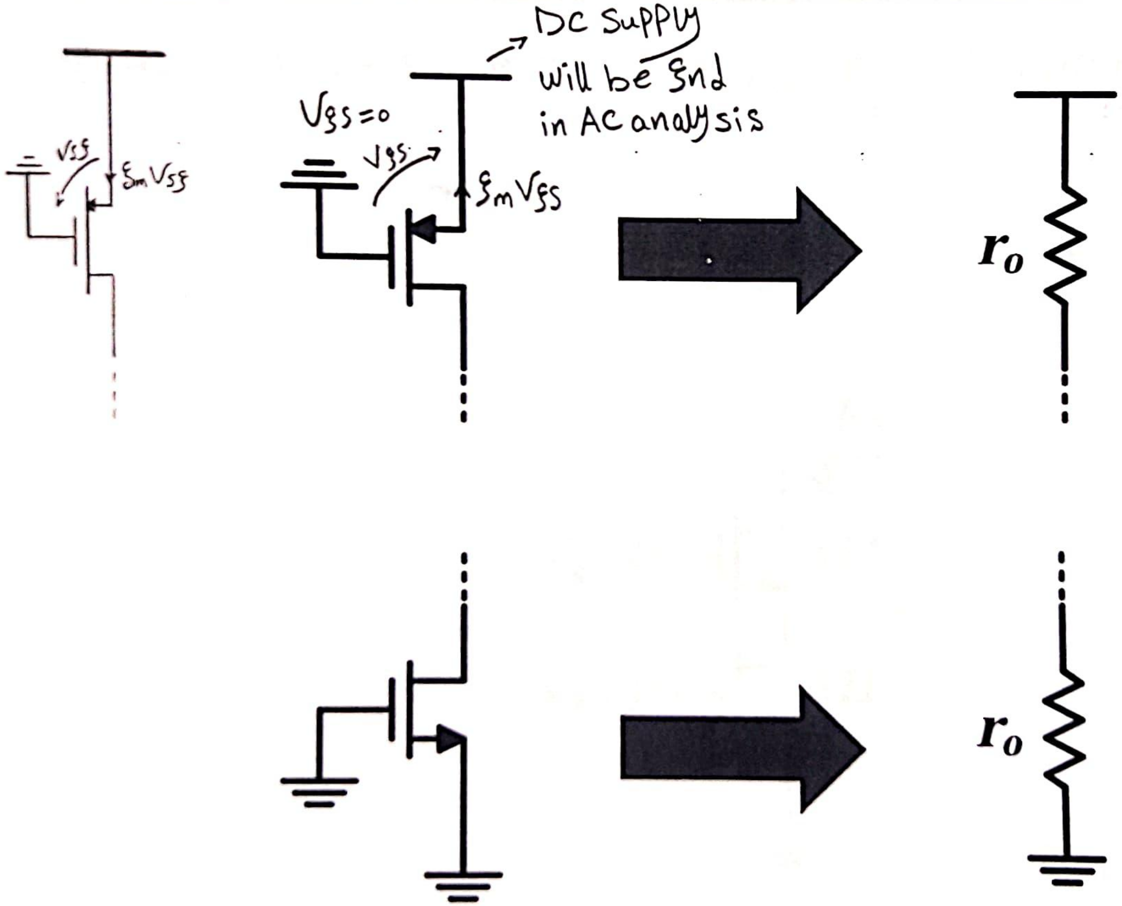
• MOSFT is basically (current source + output resistance)

→ The Current Source ($g_m V_{GS} + g_{mb} V_{BS}$) = zero

∴ The MOSFT will be only a resistance (load)

• "Active load": active element but behave as a load.

Active Load (Source OFF)

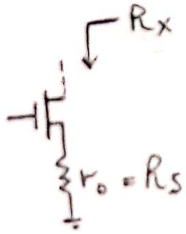


Quiz

- Assume M1 and M2 have the same g_m and r_o, $g_m r_o \gg 1$, and neglect body effect
- Find R_X

DC Source

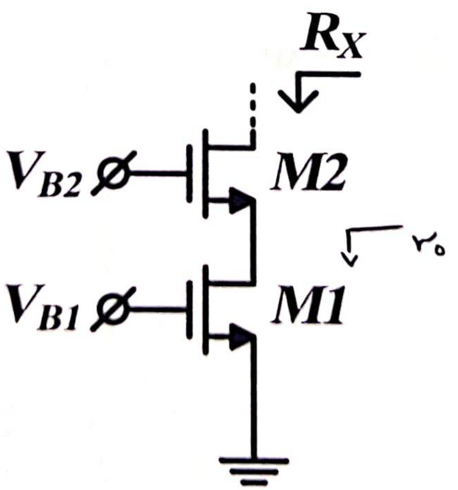
- $R_{LFD} = r_o [1 + (g_m + g_{mb}) R_S]$
- for M_1 : $R_{LFD_1} = r_o$ (active load)



$\therefore R_{LFD} = r_o [1 + (g_m + \cancel{g_{mb}}) r_o]$

$\because g_m r_o \gg 1$

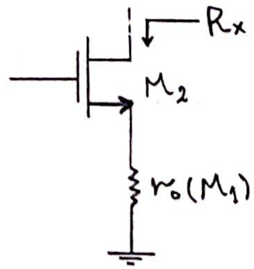
$\therefore R_{LFD} = g_m r_o \cdot r_o = g_m r_o^2$



※ If I have two transistor I should begin with that connected to gnd (NMOS) and that connected to VDD (PMOS).

★ Sun, Aug, 13, 2022 :

- M_1 is special case as in AC the gate & the source are connected to the 'Gnd' so, 'Active Load'



- $R_x = R_{LFD}(M_2) = r_o [1 + (g_m + g_{mb}) R_S]$

$\because$ neglect body effect i.e. $g_{mb} = 0$

$\therefore R_x = r_o [1 + g_m r_{o(M_1)}]$

$\because g_m \cdot r_o \gg 1$, $r_o(M_2) = r_o(M_1)$

$\therefore R_x = r_o [g_m r_o]$

$\therefore R_x = g_m \cdot r_o^2$

Looking From Source

1- ∵ the gate is AC gnd → ∴ $V_{gs} = V_{bs}$
∴ $(g_m + g_{mb})$

- $v_{gs} = -v_x$, g_m and g_{mb} add, and $g_m r_o \gg 1$
- 3- Apply KCL at S

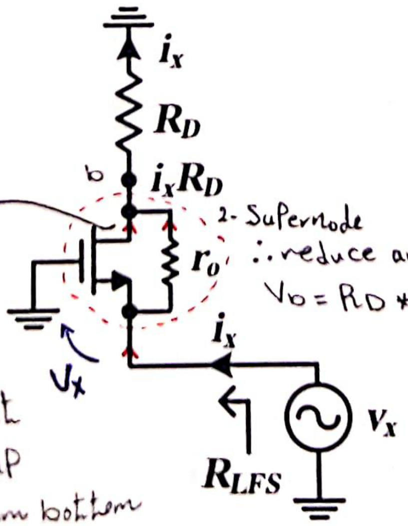
i_{in} $\quad$ $i_{transistor}$ (VCCS) $\quad$ i_{r_o} (Ohm's Law)

$$i_x = (g_m + g_{mb})v_x + \frac{v_x - i_x R_D}{r_o}$$

equation with no unknown but i_x & V_x ☑

$$R_{LFS} = \frac{v_x}{i_x} = \frac{1}{g_m + g_{mb} + \cancel{\frac{1}{r_o}}}\left(1 + \frac{R_D}{r_o}\right) \approx \frac{1}{g_m + g_{mb}}\left(1 + \frac{R_D}{r_o}\right)$$

$g_m r_o \gg 1$
$g_m \gg \frac{1}{r_o}$



$g_m V_x$
↓
$g_m + g_{mb}$

2- Supernode
∴ reduce an unknown
$V_D = R_D * i_x$ (same as the i/P of the supernode)

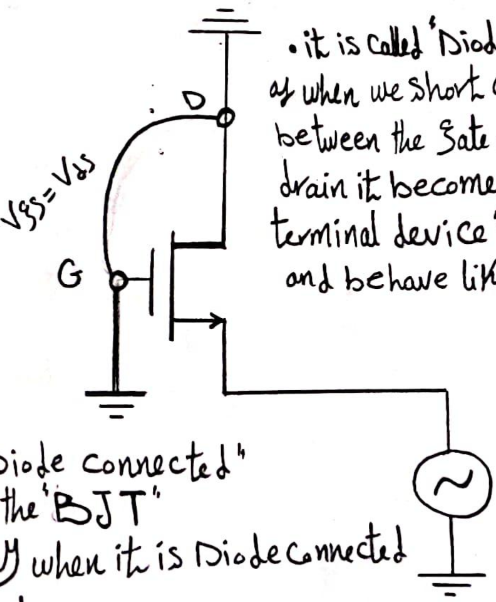
3.5 the current flows in the direction of the volt
so, as V_x is from down to up
∴ the current will also flow from bottom to up.

1.5 we put V_x @ source
$R_{LFS} = \frac{V_x}{i_x}$

Looking From Source

$$R_{LFS} \approx \frac{1}{g_m + g_{mb}}\left(1 + \frac{R_D}{r_o}\right)$$

2: "Diode Connected"
↳ Gate & Drain are AC S.C.



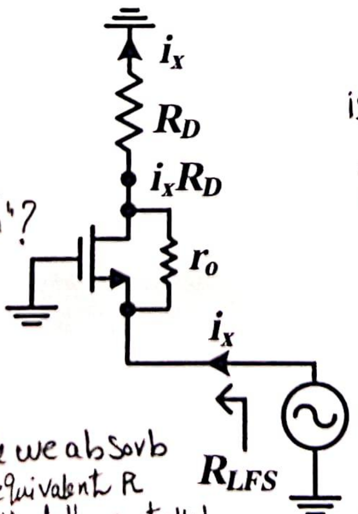
• it is called 'Diode Connected' as when we short circuit between the gate and the drain it becomes 'two-terminal device' and behave like a diode

- Special case: $R_D = 0$ ➔ **diode connected**

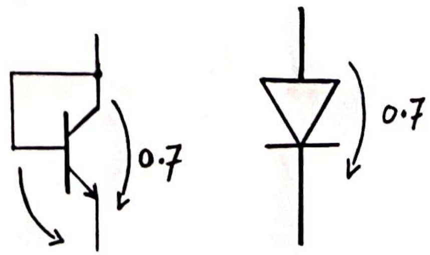
$$R_{LFS} \approx \frac{1}{g_m + g_{mb}}$$

- **Source is a low impedance node (L.I.N.)**

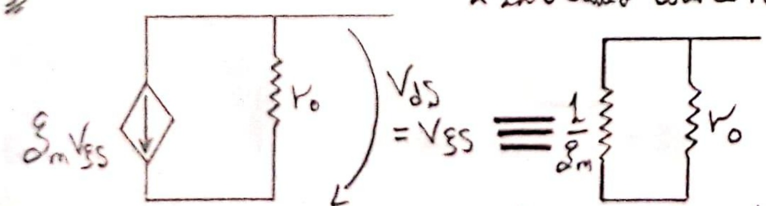
1: If: $R_D=0 \rightarrow R_{LFS} = \frac{1}{g_m + \cancel{g_{mb}}^{\to 0}}\left(1+\cancel{\frac{R_D}{r_o}}^{\to 0}\right)$
by neglecting the body effect
$\therefore R_{LFS} = \frac{1}{g_m}$ which is very small. (low impedance)



• This name 'Diode connected' is inherited from the 'BJT'
• In BJT actually when it is Diode connected it will be a diode



3: ★ It's called 'Source Absorbtion'?



This is the source absorbtion like we absorb the current source and replaced by equivalent R

$R_Z = \frac{V_Z}{I_Z} = \frac{V_{DS}(V_{GS})}{g_mV_{GS}} = \frac{1}{g_m}$ • WHY? - As the controlling volt of the controlled source is the same as the voltage across the controlled source so, it won't be controlled source anymore it will be a resistance.

for current source

4: But: $R_{LFS} = \frac{1}{g_m+g_{mb}}$ doesn't contain r_o ?
as from the previous approximation $r_o >> \frac{1}{g_m}$
$\therefore r_o \parallel 1/g_m = 1/g_m$. (but to be more accurate consider r_o especially if $g_m \cdot r_o$ is small)

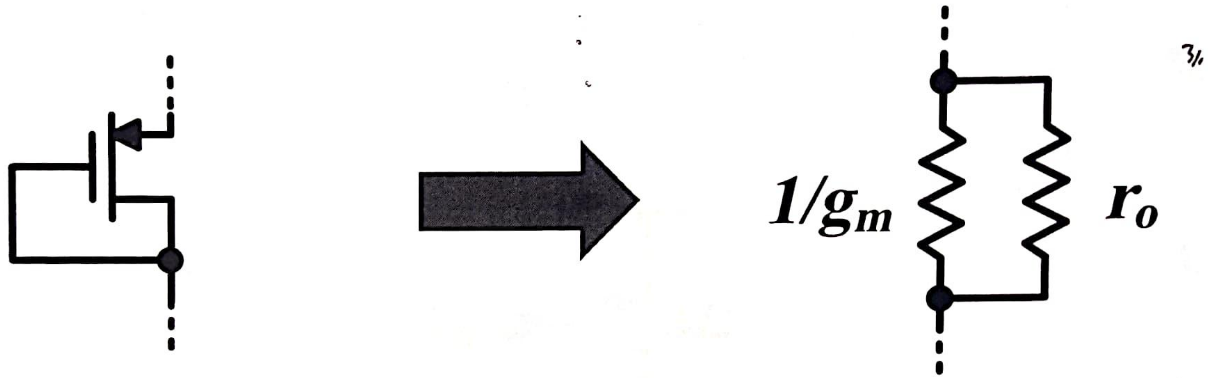
Diode Connected (Source Absorption)

- Always in saturation ($V_{DS} = V_{GS} > V_{ov}$)
- Body effect: $g_m \rightarrow g_m + g_{mb}$ (if G is ac gnd)

4/5. We know are talking about large signal as we are talking about saturation but the below equivalent circuits are in small signal

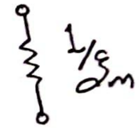
5/ $\because V_{DS} = V_{GS}$, $V_{GS} = V_{th} + V_{ov}$

$\therefore V_{DS} > V_{ov}$



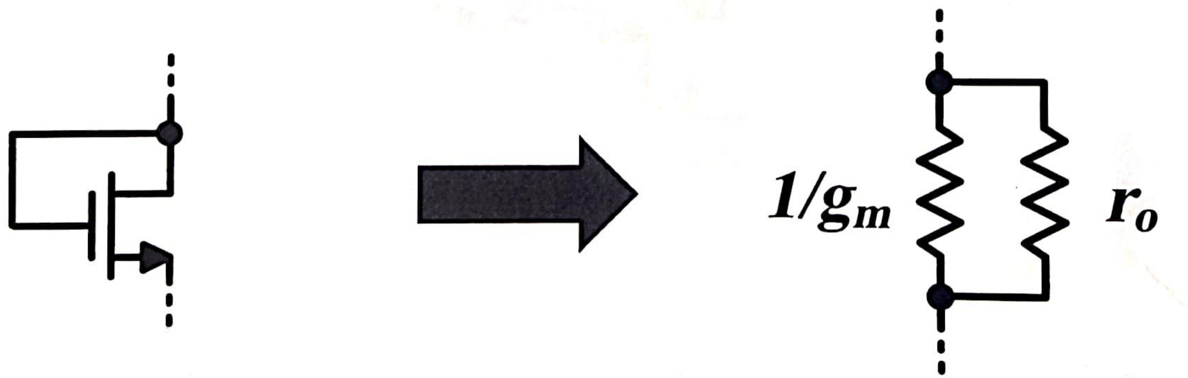
3/ • if $g_m \cdot r_o >>> 1$

$\therefore$ this circuit is equivalent to



1/ * We can apply "Diode Connected" if the Gate & the Drain are S.C.

• It's not a must that both of them are connected to "gnd" but the condition is that they must have the same "AC Voltage"



Quiz

- Assume M1 and M2 have the same r_o, $g_m r_o \gg 1$, and neglect body effect
- Find R_X

★ $R_{LFD} \cong r_o[1+g_m R_S]$

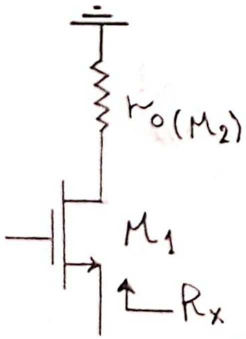
★ $R_{LFS} \cong \frac{1}{g_m}\left[1+\frac{R_D}{r_o}\right]$

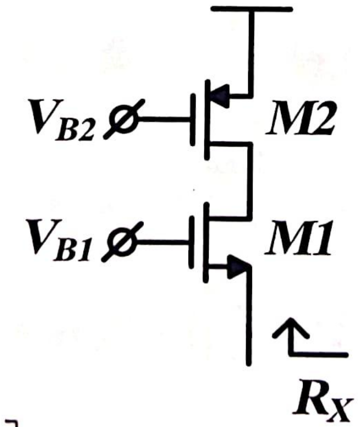
• first I'll start with the MOSFET connected to VDD (M_2)

∵ the Source & the Gate are AC short circuit

∴ Active Load

∴ $R_{LFD} = r_o$





$$R_x = R_{LFS} = \frac{1}{g_m}\left[1+\frac{R_D}{r_o}\right] = \frac{1}{g_m}\left[1+\frac{r_o}{r_o}\right]$$

$$\therefore R_x = \frac{2}{g_m}$$

Quiz

- Assume M1, M2, and M3 have the same g_m and r_o, $g_m r_o \gg 1$, and neglect body effect
- Find R_X

• $R_{LFD}(M_3) = r_o$

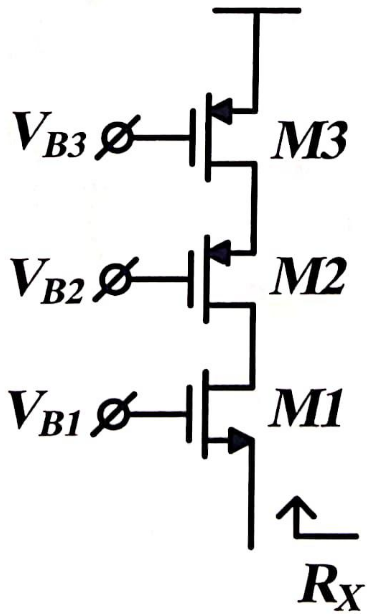
• $R_{LFD}(M_2) = r_o\left[1 + g_m R_S\right] = g_m r_o^2$

• $R_x = R_{LFS}(M_1) = \frac{1}{g_m}\left[1 + \frac{R_D}{r_o}\right]$

$\therefore R_x = \frac{1}{g_m}\left[1 + \frac{g_m \cdot r_o^{\cancel{2}}}{\cancel{r_o}}\right]$

$= \frac{1}{g_m}\left[g_m \cdot r_o\right]$

$\therefore R_x = r_o$



?/ You told us before that the source is low impedance node and R_{LFS} here is 'r_o' which is high impedance.

?/ Actually: $R_{LFS} = \frac{1}{g_m}\left(1 + \frac{R_D}{r_o}\right)$

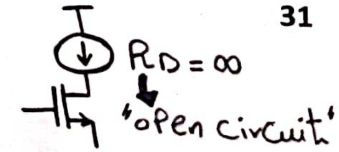
• in normal circuits $R_D << r_o$ which will results $R_{LFS} \sim \frac{1}{g_m}$ which is low impedance.

→ But here R_D isn't a normal resistance it's "$g_m (r_o)^2$" → Enormous resistance

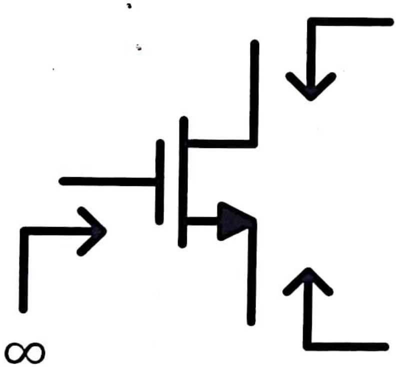
• So, the source is L.I.N except if the drain resistance is very large

→ even the opposite case:

• Sometimes when you look from the source you see infinity, HOW?!



Rin/out Shortcuts Summary



$r_o[1+(g_m+g_{mb})R_S]$

H.I.N.

• Special case: "$R_S=0$"

★ Active Load

$R_{LFD}=r_o$

"Source off"

as $V_{GS}=0$ $\cancel{VCCS}$

∞

At low frequencies **ONLY**

• as @ high frequency there will be capacitance and you should consider

★ $\frac{1}{\omega C}$

$$\frac{1}{g_m+g_{mb}}\left(1+\frac{R_D}{r_o}\right)$$

L.I.N.

except

• if R_D is very large.

• Special case: "$R_D=0$"

★ Diode Connected

$R_{LFS}=\frac{1}{g_m}$

"Source Absorption"

as $V_{GS}=V_{DS}$

• So, VCCS → $1/g_m$

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- ❑ Recapping previous key results
- ❑ Why amplifiers?
- ❑ Basic amplifier operation
- ❑ Basic amplifier analysis
- ❑ Rin/out shortcuts
  - Looking from drain
  - Looking from source
- ■ GmRout method
- ❑ Basic amplifier topologies
  - Common Source (CS)
  - Common Gate (CG)
  - Common Drain (CD) – Source Follower (SF)
- ❑ Large signal behavior

Amplifier Model

3/. ☐ Rin/out

$$R_{in} = \frac{v_{in}}{i_{in}}$$ → look from the i/p port

• Thevenin resistance
we can get by deactivation all the independent sources.

$$R_{out} = \frac{v_x}{i_x} \ @\ v_{in} = 0$$

• look from the o/p port
actually it's 'Thevenin model'

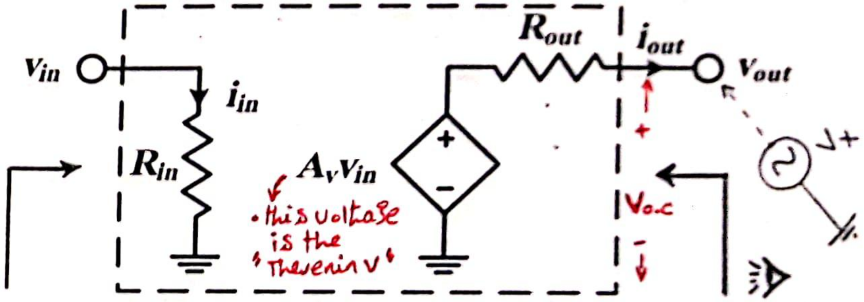
☐ O.C. voltage gain (Thevenin model)
3/.

$$v_{out,oc} = v_{Thevenin} = A_v v_{in}$$

• as @ open circuit
i_{out} = zero
& voltage drop on R_{out} = zero
so, $V_{out,oc} = A_v V_{in}$

$$A_v = \frac{v_{out,oc}}{v_{in}}$$ → $A_{v,oc}$

4/. while solving circuit will we use this equation to get the gain?
- Actually No, we want to model the circuit @ the o/p by Norton model instead of thevenin.



½ ★ Voltage Amplifier Model
→ we called it voltage amplifier

• as: we model the amplifier by input an input voltage "Vin" and take 'Vout' by multiplying by a gain 'Av'.

• Actually this is not the only case as sometimes the input is a current, sometimes the output is a current, so, there are many different cases.
★ But the 'Voltage Amplifier Model' is the most common case.

Amplifier Model

- Transconductance (Norton model)

5. $\underline{G_m}$: is the transconductance for a whole circuit / whole amplifier which can include 1, 2, 10, 20 transistors.

4. $i_{out,sc} = i_{Norton} = G_m v_{in}$

$$G_m = \frac{i_{out,sc}}{v_{in}}$$

$\underline{g_m}$: is the transconductance of a single transistor.

- Thevenin ⇔ Norton

@Thevenin model i_N @Norton model

to relate both models to each other. 4.

3. $v_{out,oc} = A_v v_{in} = (\overbrace{G_m v_{in}}^{i_N}) R_{out}$

4. we compute the voltage gain 'A_v' in two steps:
1- get G_m from $\frac{i_{out,sc}}{v_{in}}$ 2x
2- $R_{out} \rightarrow R_{Thevenin}$

$$\boxed{A_v = \frac{v_{out,oc}}{v_{in}} = G_m R_{out}}$$

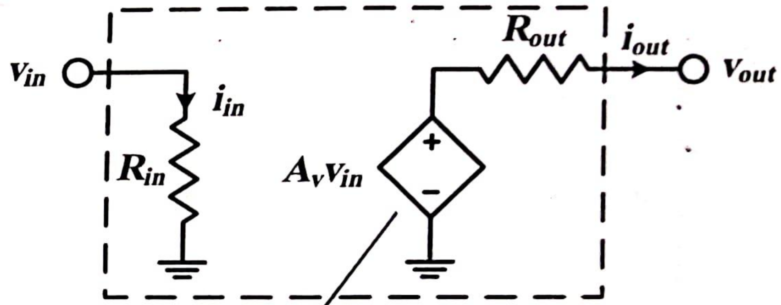
4. ★ the most important equation

5. - S.C. Current Gain

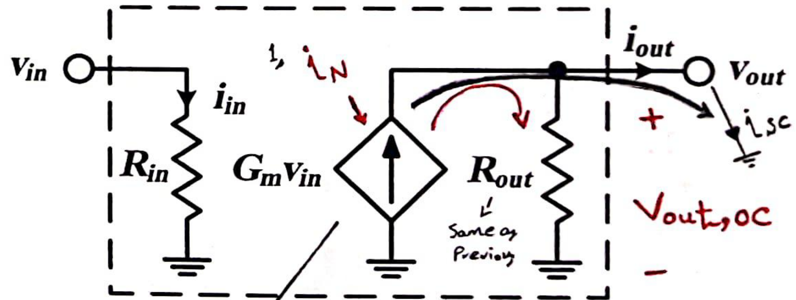
5. So, by computing G_m you kill two birds with one stone
→ ★ $R_{out} \rightarrow A_v$
→ ★ $R_{in} \rightarrow A_i$

$$\boxed{A_i = \frac{i_{out,sc}}{i_{in}} = \frac{i_{out,sc}}{v_{in}/R_{in}} = G_m R_{in}}$$

$$\frac{i_{out,sc}}{v_{in}} = G_m$$



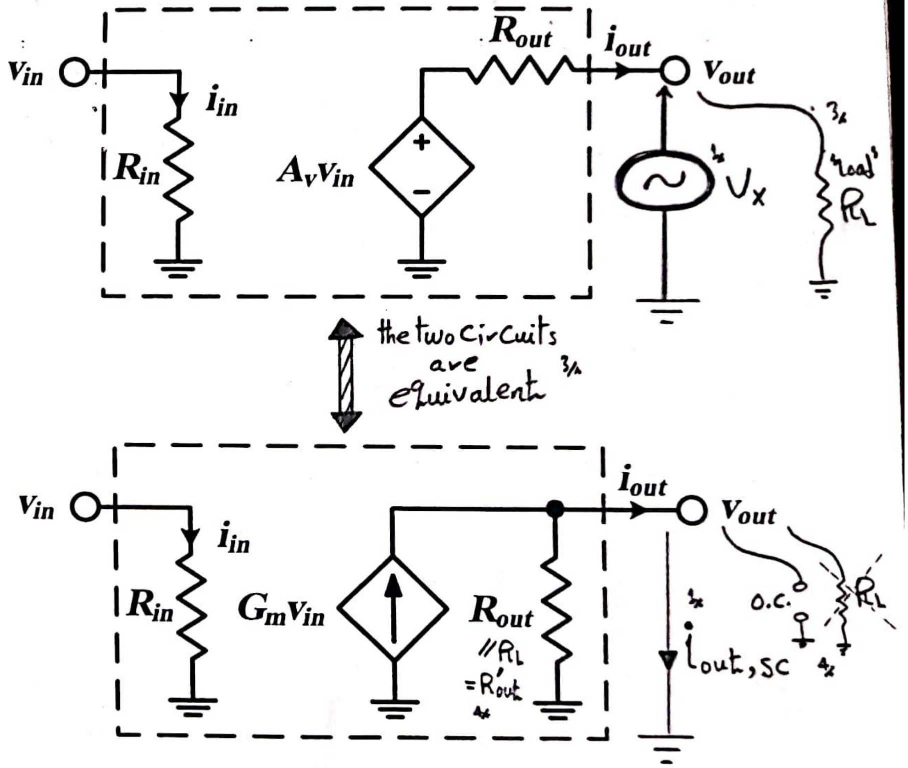
3. "VCVS"



3. "VCCS"

Why GmRout?

$$R_{in} = v_{in}/i_{in}$$
$$R_{out} = v_x/i_x \text{ @ } v_{in} = 0$$
$$G_m = i_{out,sc}/v_{in}$$
$$A_v = G_m R_{out}$$
$$A_i = G_m R_{in}$$



- Divide and conquer
  - Rout simplified: $v_{in} = 0$
  - Gm simplified: $v_{out} = 0$
  - We already need Rin/out and Gm
  - We can quickly and easily get Rin/out from the shortcuts

But you didn't tell us an important condition to consider which is Av is the Av,o.c. So, if we have a load every thing will change. Don't worry Dude, it's very simple. Look @ the Norton model if we have a load resistance what will make you happy? - I'll be happy if the o/p is open circuit. So, put R_L inside the amplifier where Rout becomes $R'_{out} = R_{out} // R_L$
∴ $A_{v,oc} = G_m \cdot R'_{out}$ where R'_{out} is all the resistances connected to the o/p node.

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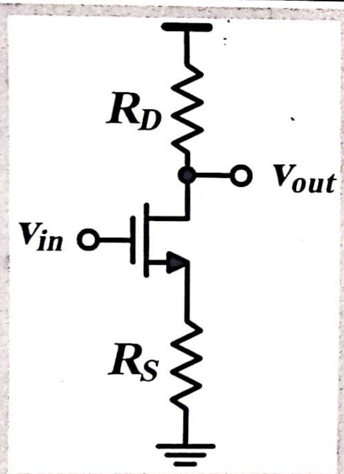
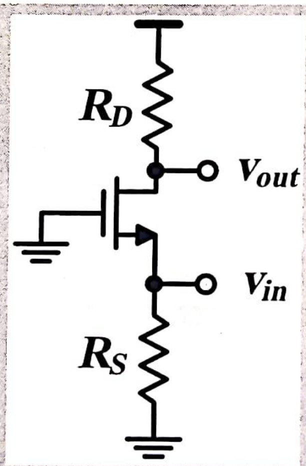
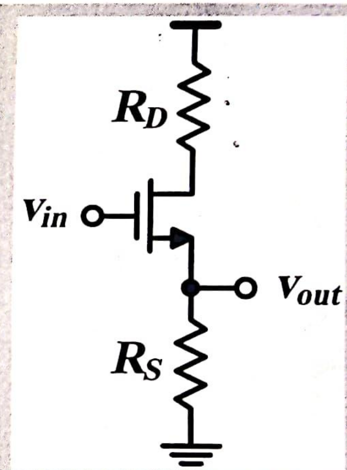
Basic Amplifier Topologies

	Common Source (CS)	Common Gate (CG)	Common Drain (CD) Source Follower (SF)
			
	Voltage & current amplifier	Voltage amplifier Current buffer	Voltage buffer Current amplifier
In	*G*	*S*	*G*
Out	*D*	*D*	*S*

1. ★ Divide & Conquer:
$A_v = G_m R_{out}$
✓ × ✓

Common Source (CS)

3. ☐ Apply KCL at S noting that $v_{gs} = v_{in} - (-i_{out,sc} R_S)$

S.C. ← o - - V_S / r_o

$$i_{out,sc} + g_m(\underbrace{v_{in} + i_{out,sc} R_S}_{V_{gs}}) + g_{mb}(\underbrace{i_{out,sc} R_S}_{V_{bs}}) + \frac{i_{out,sc} R_S}{r_o} = 0$$

• Current through r_o 2. by ohm's Law

$+ g_m r_o >> 1$

$$\boxed{G_m = \frac{i_{out,sc}}{v_{in}} \approx \frac{-g_m}{1 + (g_m + g_{mb}) R_S}}$$

→ Norton Current

Same

4. no S.C. but we connect 4. a test source V_x then compute V_x/i_x

$$R_{out} \approx R_D || \underbrace{r_o[1 + (g_m + g_{mb}) R_S]}_{R_{LFD}}$$

$$A_v = G_m R_{out}$$

5. Some Special Cases:

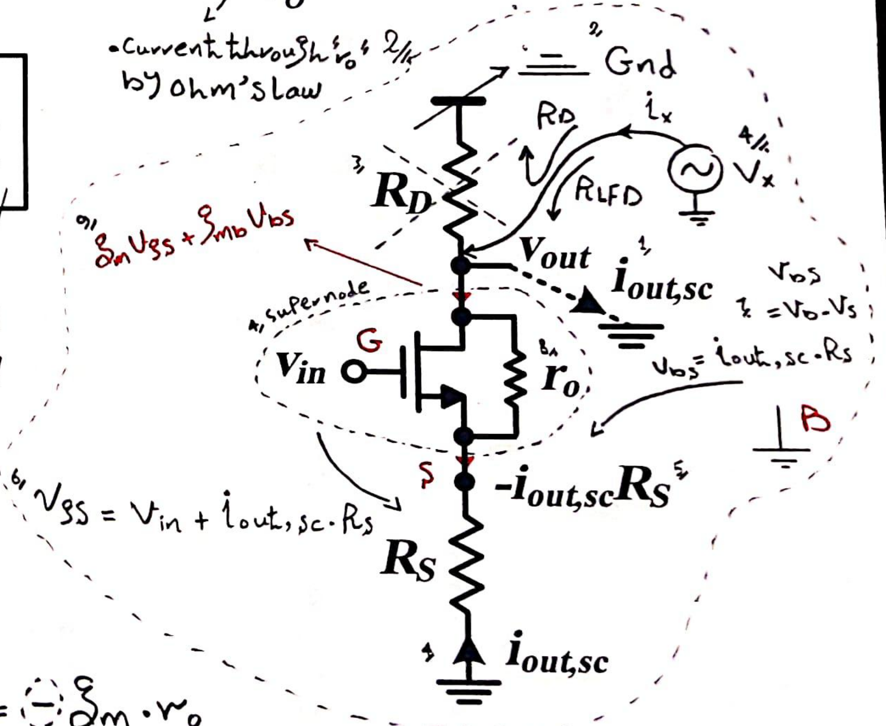
intrinsic gain

☐ If R_D is ac o.c.: $A_v = -g_m r_o$ if we bias with C.S I_D

☐ If $R_D \ll R_{LFD}$: $A_v \approx \frac{-g_m R_D}{1+(g_m+g_{mb}) R_S}$

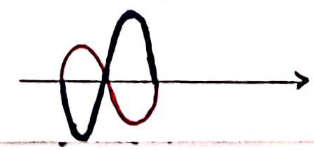
☐ If $R_S = 0$: $A_v = -g_m (R_D // r_o)$

$\therefore A_v = -g_m \cdot r_o$

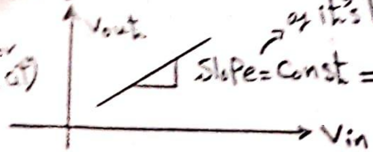


6. $A_v = (-) g_m \cdot r_o$

180° Phase shift



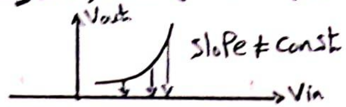
3/. The second special thing is that: the gain is "Linear":



(we for simplicity)

as it's linear → Slope = Const $= \frac{\Delta V_{out}}{\Delta V_{in}} = A_v \neq f(V_{in})$

9/. So, to have a linear relation for the amplifier the gain should be constant (i.e. dependless on the input)



slope ≠ const $\therefore A_v = f(V_{in})$
∴ non linear gain

10/. You told us that $\frac{-R_D}{R_S}$ is a linear gain, well but before ignoring the term of $1/g_m$ who said that $-\frac{\text{Drain Res}}{1/g_m + \text{Source Res}}$ is not linear

10/. • we assume an approximation that the gain is linear around the operating point, if there is very small signal change.

★ "g_m" depends on "bias current"
"Bias current" depends on the input voltage"
★ linearization of the circuit doesn't means it's linear, there are still non linear characteristics.

Common Source (CS)

7/. You should never make your design to depend on absolute values, for ex.

$R_D \sim 1K\Omega \pm 20\% \rightarrow$ large variations

$\frac{5(1K \mp \Delta)}{1K \mp \Delta} = 5$ (→ 5 series "R_S") ∴ Designing with ratios is more robust

this illustration is for $\frac{5K}{1K}$ → we implement 5K with 5 series 1K from the same type (for better matching)

$$G_m = \frac{i_{out,sc}}{v_{in}} \approx \frac{-g_m}{1 + (g_m + g_{mb})R_S}$$

$$R_{out} \approx R_D || r_o[1 + (g_m + g_{mb})R_S]$$

$$A_v = G_m R_{out}$$

2/. ∴ g_{mb} as $V_{BS} = 0$

$\therefore G_m = \frac{-g_m}{1+(g_m)R_S} \left(\div g_m\right) \rightarrow G_m = \frac{-1}{1/g_m + R_S}$

$\therefore R_{out} = R_D \,//\, r_o \,[1+(g_m)R_S]$

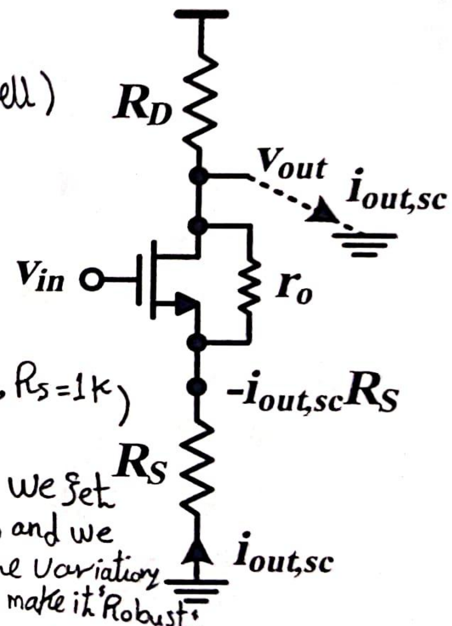
1/. ❑ If S and B are ac connected (for PMOS): (as PMOS is placed inside it's well)

2/. $A_v \approx \frac{-R_D||R_{LFD}}{\frac{1}{g_m} + R_S} = -\frac{Drain\ Res.}{\frac{1}{g_m} + Source\ Res.}$

3/. ❑ If $R_S \gg \frac{1}{g_m}$ & $R_D \ll R_{LFD}$: $A_v \approx \frac{-R_D}{R_S}$ → Linear gain! (for ex. if $R_D = 5K, R_S = 1K$) ∴ $A_v \sim -5$

6/. what's special in this eq. is that we set the gain as a ratio of two resistors, and we know that in analog design as a result of the variations in the IC, designing the design as a ratio of parameters make it "Robust".

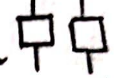
12/. ❑ R_S reduces G_m → **Source degeneration**
- But improves linearity



4/. we can use the assumption of S and B are ac connected for:
• PMOS • NMOS (triple well)

5/. In the simulation: in the small signal parameters g_{mb} will have a value, but does this value have a meaning or it's meaningless it depends on the connection of the source & the body

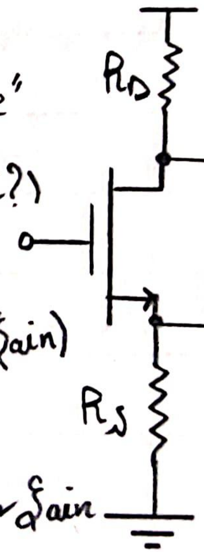
11/ Designing by a ratio guarantees that the gain is linear across the variations.

• Variations $1K \pm 20\%$ ← ★ Variations Vs. Mismatch → • If in the layout 
mean that we can't control the absolute value of the component (we can't know accurately the absolute values) ← or same variations

• Their absolute value will differ but they will still the same, will they be exactly the same? - of course No

• There will be a small error (called the mismatch) this inherent mismatch is a result that the machines used to manufacter the ICs have their noise and tolerences. Actually In ICs as the devices are very close to each other (dimensions by μm)
• Mismatch can be better than 1% (< 1%) so the error will be < 1% not > 20% as ($1K \pm 20\%$)

12/ R_S : Degeneration Resistant



• we called this amplifier "Degenerated Common Source"

→ R_S reduces G_m so, reduces the gain (so, why we put it?)
↳ we use it as it "improves the linearity"

@ the ultimate case it makes the gain ratio of resistors $\frac{-R_D}{R_S}$ (linear gain)
and even if we don't neglect $\left(\frac{1}{g_m}\right)$ it still reduce the effect of the variations occur in g_m over the amplifier gain.

★ trade-off ⟨ Gain / Linearity and this trade-off is always there in the feedback systems and R_S is doing some sort of feedback we can have a look later when we study feedback.

★ In this ideal case: Input Impedance $= \infty$ so, Current Gain $A_i = -G_m R_{in} = \infty$ → It's a rational result as it absorbs no current.
★ Notice that when we calculated "R_{out}" we took into consideration all the resistances connected to the output node.

∴ Same technique, write the analysis on the schematic then single KCL

1/ Divide & Conquer

$A_v = G_m R_{out}$

output → s.c. input → s.c.

Common Gate (CG)

3/ ☐ Apply KCL at D noting that $v_{gs} = v_{bs} = 0 - v_{in}$

7/ when we calculate Rout
$R_{out} = \frac{V_x}{i_x}\Big|_{V_{in}=0}$ Deactivation to the input source

∴ we omit R_S

So, when looking we won't see anything but 'r_o'

$$i_{out,sc} + (g_m + g_{mb})(-v_{in}) - \frac{v_{in}}{r_o} = 0$$

4/ $$\boxed{G_m = \frac{i_{out,sc}}{v_{in}} \approx g_m + g_{mb}}$$

6/ Rout = to parallel resistances $R_{out} \approx R_D || r_o$ (**why**?)

@ the output node 1- up: R_D, 2- down: supposed to be R_{LFD} like 'CS' but instead we are seeing 'r_o' why?

$$A_v = G_m R_{out}$$

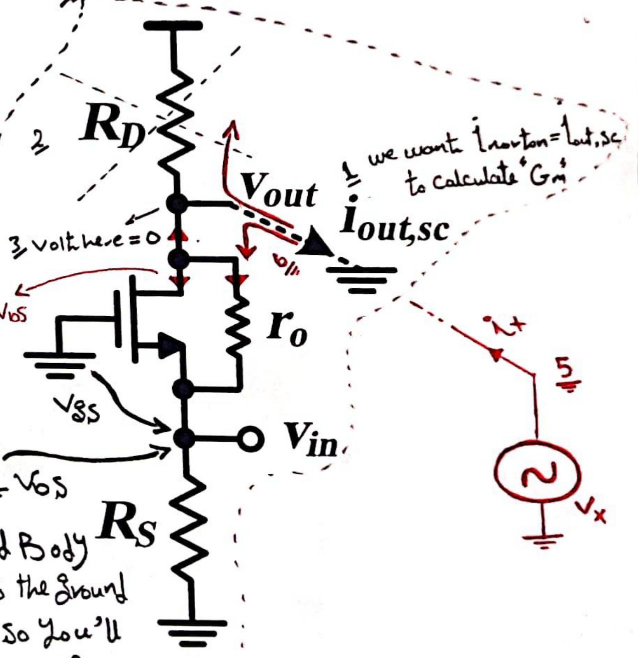
8/ ★ In this case: "g_{mb}" gives bigger gain than the 'intrinsic gain'

8/ ☐ If R_D is ac o.c.: $A_v = (g_m + g_{mb})r_o$

9/ ☐ If $R_D \ll r_o$: $A_v \approx (g_m + g_{mb})\boldsymbol{R_D}$

10/ ☐ If S and B are ac connected: $(g_m + g_{mb}) \to g_m$

11/ ☐ Note that $A_i = G_m R_{in} <\approx$ **1 (Current Buffer)**



• Both Gate and Body are connected to the ground so $V_{gs} = V_{bs}$ so you'll always see g_m and g_{mb} are added together in the equations
unlike CS amplifier we saw $(g_m + g_{mb})$ in the denominator but in the nominator only g_m.

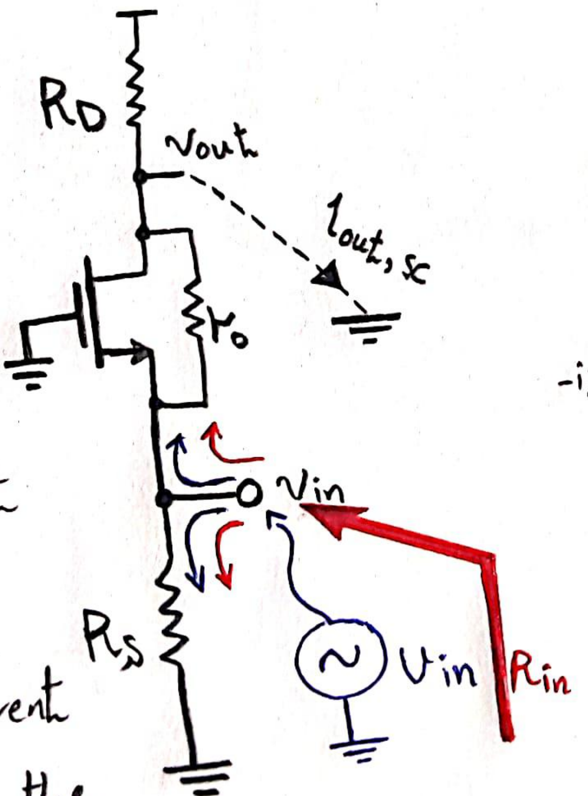
9.5/ Note that the gain is positive i.e. no phase inversion like CS.

11

★ one of the important notes is that the Common Gate (CG) is voltage amplifier but "Current Buffer", why?

Sense

Equations



• We have the input @ the source and the output @ the drain

• and we know that the current @ the gate = zero and the current of the source is roughly equals to that of the drain so, it's rational to say that it won't amplify the current

★ the currents flowing through both the source & the drain are the same.

★ even Practically (the gain < 1)

• As Part of the current coming from the input source will flow through "R_S" and the rest flow through source then drain.

• Short circuit current gain

$A_i = G_m \cdot R_{in}$

- if there is no body effect (for simplicity) $= g_m$

$R_{in} = R_S \,//\, R_{LFS}$ ⟹ the biggest value for this expression occurs when "$R_S = \infty$"

• Assume $R_D \ll r_o$

$\therefore R_{LFS} = 1/g_m$

So, when $R_S = \infty$

$A_i = g_m * \frac{1}{g_m} = 1$

★ So with R_S there

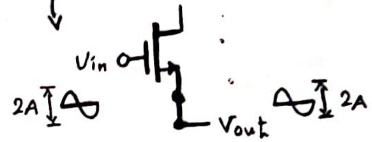
$A_i < 1$ (intuition results verified) successfully #

9/ Same as Previous
Gm Rout
✓ ✓

Common Drain (CD) – Source Follower

15/ It's called "Source Follower" as the source terminal follows the input, as since '$A_v \simeq 1$' therefore '$V_{out} \simeq V_{in}$'

$A_v = \frac{\Delta V_{out}}{\Delta V_{in}} = \frac{V_{out}}{V_{in}}$ ∴ the source terminal has the same changes occur @ the output



- Apply KCL at D

6/

$- (0 - i_{out,sc} R_D)$

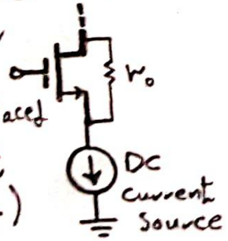
$$+\underbrace{i_{out,sc}}_{\text{entering the node}} \underbrace{-\, g_m v_{in}}_{\text{leaving the node}} + \frac{i_{out,sc} R_D}{r_o} = 0$$

$$\boxed{G_m = \frac{i_{out,sc}}{v_{in}} \approx \frac{g_m}{1 + R_D/r_o}}$$

7/ if $R_D \ll r_o$

∴ $G_m \approx g_m$ same as "CG amplifier"

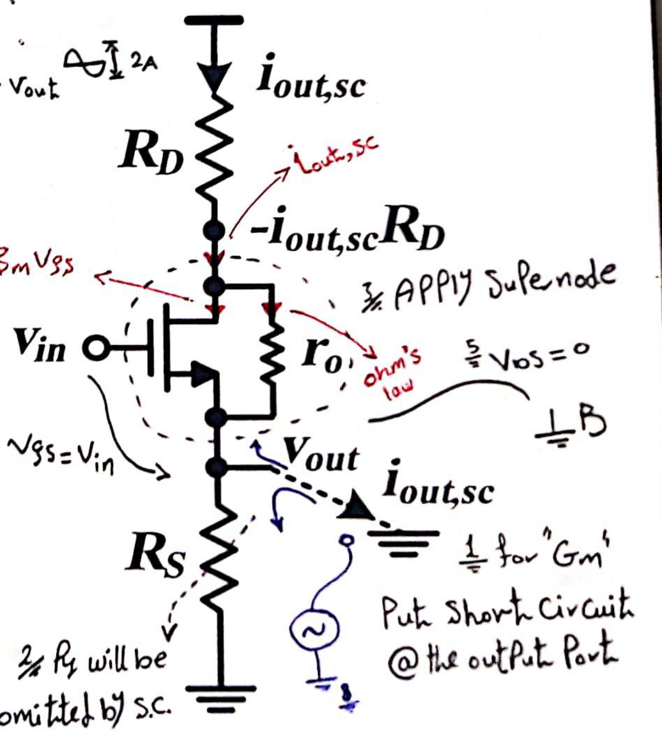
9/ the biggest value for Rout when R_S = O.C. which means when replaced by DC current source



$\frac{g_m}{1 + R_D/r_o} * \frac{1}{g_m + g_{mb}}\left(1 + \frac{R_D}{r_o}\right)$

8/ $$R_{out} \approx R_S || \underbrace{\frac{1}{g_m + g_{mb}}\left(1 + \frac{R_D}{r_o}\right)}_{R_{LFS}}$$

$$A_v = G_m R_{out}$$



3/ Apply Supernode

5/ $V_{DS} = 0$

4/ $V_{gs} = V_{in}$

1/ for "Gm" Put Short Circuit @ the output Port

2/ R_S will be omitted by S.C.

10/ - If $R_S \gg R_{LFS}$: $A_v \approx \frac{g_m}{g_m + g_{mb}} < 1$ → and this is the largest gain

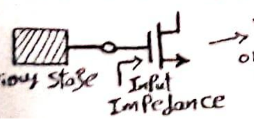
11/ - If S and B are ac connected (for PMOS): (no body effect)

$$A_v \approx \mathbf{1}\ \textbf{(Voltage buffer)}$$

12/ Practically < 1 as the current source will have output resistance

13/ So, what is the benefit of the CD amplifier?

- It isolates the output from the output.



→ There is no "Loading effect" on the Previous stage as it'll same "infinite impedance"

→ The output will see low output impedance

Buffer → Rin ↑↑ → Rout ↓↓

14/ Also another advantage is that CD Provides "current gain" and Provides current
↳ Ideally absorbs zero current as Rin ↑↑

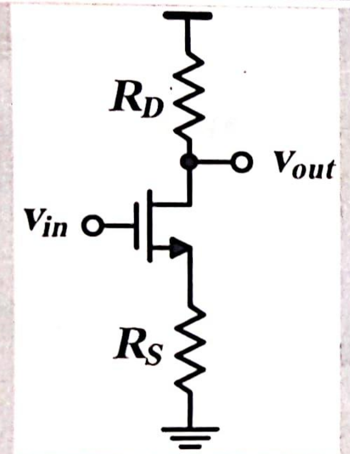
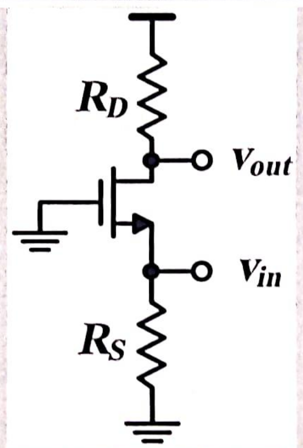
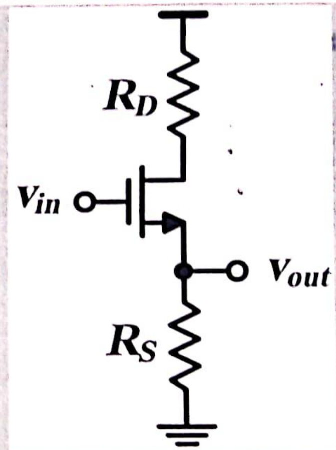
3/. $\bullet\ g_m \cdot r_o >> 1$

$r_o >> \frac{1}{g_m}$

anything of r_o order is "high impedance"

anything of $1/g_m$ order is "Low impedance"

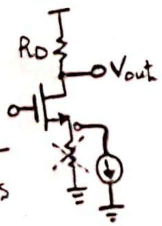
Summary of Basic Topologies

	CS	CG	CD (SF)
			
	Voltage & current amplifier	Voltage amplifier Current buffer	Voltage buffer Current amplifier
Rin	∞ • large Rin	$R_S \parallel \frac{1}{g_m + g_{mb}}\left(1 + \frac{R_D}{r_o}\right)$ • Low Rin as (R_{LFS}). ↳ except if $R_D \uparrow\uparrow$ in some cases	∞
Rout	$R_D \parallel r_o[1 + (g_m + g_{mb})R_S]$ • Also large Rout as (R_{LFD})	$R_D \parallel r_o$ • High Rout as (R_{LFD})	$R_S \parallel \frac{1}{g_m + g_{mb}}\left(1 + \frac{R_D}{r_o}\right)$ • Low Rout
Gm	$\frac{-g_m}{1 + (g_m + g_{mb})R_S}$	$g_m + g_{mb}$	$\frac{g_m}{1 + R_D/r_o}$

1/. ★ for CS if we replace "R_D" with DC current source will the amplifier operates well?
- Yes and the gain will increase as $R_{out} = (R_D \parallel) r_o [1+(g_m+g_{mb})R_S]$

★ What about replacing R_S?
- The answer is no it will not work. why? $\frac{-g_m}{1+(g_m+g_{mb})R_S}$, $R_S \to \infty$

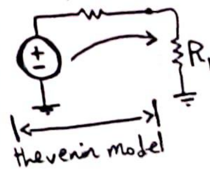
$\therefore G_m = 0$



★ بوظت الأمبليفاير
معاك واحد غيره (^-^)

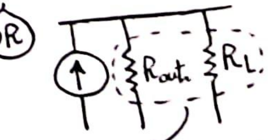
★ We'll face this case later @ Diff. Amplifier.

2/. ★ For CD:
★ for the buffer it's good to have low Rout to avoid "Loading effect"



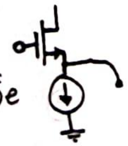
• There will be a voltage divide between Rout & R_L
• To make all the voltage goes to "R_L" we need Rout low.

OR



• if R_L is small and Rout $\therefore R_L$ will swamp Rout

5/. Also, it's better in the common drain as previously said is to replace R_S with DC current source for not distributing the current between the R_S and the load resistance or the next stage



4/. • R_D reduces the gain of CD so, it's rational not to add R_D and replace it with S.C.
• Will it operate then? - Yes, common drain means that the drain is ground @ the ac model

1/ • IN → Source
• OUT → Drain } Common Source

2/ No resistance @ the drain and even in the previous analyses.
★ In ICs we rarely use resistors but loads are implemented using transistors (every thing is expressed using transistors) and then we can replace that transistor with equivalent R.

Quiz

- The circuit below shows a CS amplifier With diode-connected load
- Find the gain using GmRout (ignore body effect and CLM). → $r_o \to \infty$, $V_A \to \infty$
  - Express the gain in terms of $(W/L)_1$ and $(W/L)_2$. → g_m can be expressed in terms of (W/L).
- This is a "linear" CS amplifier.

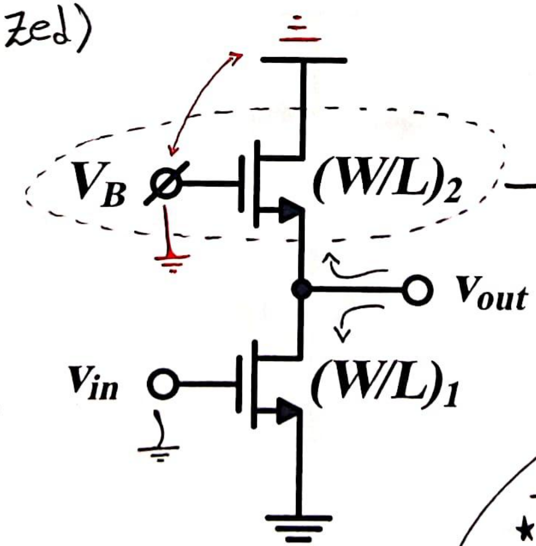
★ $G_m = \dfrac{-g_m}{1+g_m R_S}$ (Should be memorized) $R_S = 0$

$\therefore G_m = -g_{m1}$ → as M_1 as this is the Mos responsible of the amplification process or the transconductance (convert v_{in} to i_{out})

$R_{out} = \dfrac{1}{g_{m2}} \parallel r_o$ → as source off so, there is only r_o

• neglect r_o

$\therefore R_{out} = \dfrac{1}{g_{m2}} \longrightarrow \therefore A_v = -\dfrac{g_{m1}}{g_{m2}}$



→ $R_D \simeq \dfrac{1}{g_{m2}}$ • to be distinguished of g_{m1} as both are different as they have different sizing

$\therefore A_v = -\dfrac{g_{m1}}{g_{m2}} = \dfrac{\sqrt{\mu_n C_{ox} (\frac{W}{L})_1 2I_D}}{\sqrt{\mu_n C_{ox} (\frac{W}{L})_2 2I_D}} = \sqrt{\dfrac{(W/L)_1}{(W/L)_2}}$

★ Interesting as the gain is expressed as a Ratio
→ Good design depends on ratio not absolute.
★ Interesting as it ratio of sizing $\neq f(v_{in})$ i.e. "linear"
• There were many approximations
- we neglect r_o, and body effect for M_2

not very interesting untill expressing g_m with an equation

But which one? (3 expressions) the one with W/L & Current

he told me to express

→ there is a special property the current in the whole branch is the same (through M_1 & M_2)

★ Actually you won't have a great gain as g_m/g_m so, it's trade-off
Source floating

★ If you notice this amplifier is like "CMOS Inverter" in digital so, it's called "inverter amp." and it's the same circuit as the CMOS inverter and sometimes it's called "Complementary common source amp." and it's disadvantage is that it has (very poor power supply rejection) → will be discussed later

Quiz

- The circuit below shows a complementary CS amplifier (inverter amp).
- Find the gain using GmRout.

• Here this example is a bit complex as there are two amplifiers not one
→ The input enters both M_1 & M_2

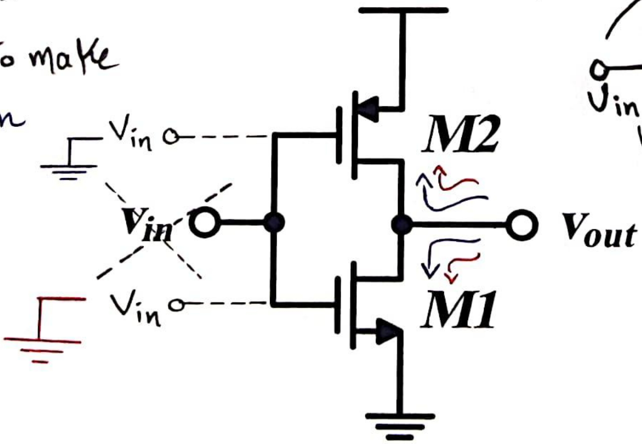
★ First solution (which will enable us to make use of the shortcuts) is the superposition

(1) $\frac{V_{out}'}{V_{in}} = G_m R_{out} = -g_{m1}(r_{o1} \parallel r_{o2})$

(2) $\frac{V_{out}''}{V_{in}} = -g_{m2}(r_{o1} \parallel r_{o2})$

∵ By sum (1) & (2)

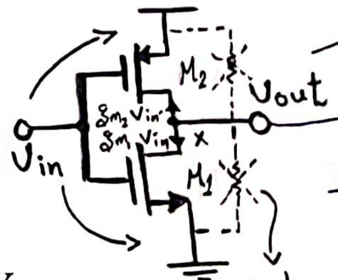
$\therefore \frac{V_{out}}{V_{in}} = -(g_{m1} + g_{m2})(r_{o1} \parallel r_{o2})$



★ Another solution is to calculate "Gm" by definition

$G_m = \frac{i_{out,sc}}{V_{in}}$

"Simply the MOS model is a current source & a resistance"



★ Apply KCL @ X

$0 = g_{m2} V_{in} + g_{m1} V_{in} + i_{out,sc}$

the two resistances are omitted as they have two grounds @ each terminal

$\therefore i_{out,sc} = -(g_{m1} + g_{m2}) * V_{in}$

$\therefore G_m = \frac{i_{out,sc}}{V_{in}} = -(g_{m1} + g_{m2})$

$\therefore A_v = G_m R_{out} = -(g_{m1} + g_{m2})(r_{o1} \parallel r_{o2})$

★ Notice that:

This amplifier gives us an important property which is increasing "Gm" instead of Gm of one transistor it gives the Gm of two transistors so, it's (Energy Efficient) → large Gm + low bias current

Outline

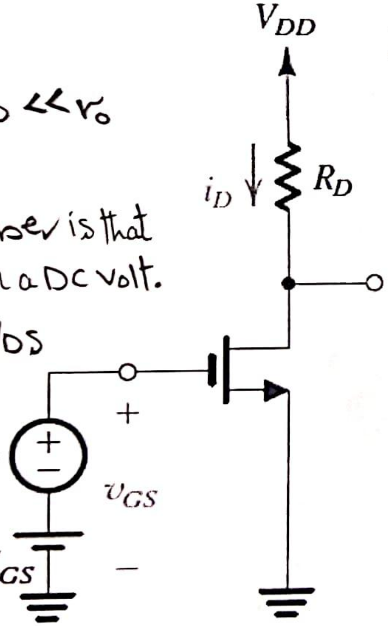
- ❑ Recapping previous key results
- ❑ Why amplifiers?
- ❑ Basic amplifier operation
- ❑ Basic amplifier analysis
- ❑ Rin/out shortcuts
  - Looking from drain
  - Looking from source
- ❑ GmRout method
- ❑ Basic amplifier topologies
  - Common Source (CS)
  - Common Gate (CG)
  - Common Drain (CD) – Source Follower (SF)
- ■ Large signal behavior

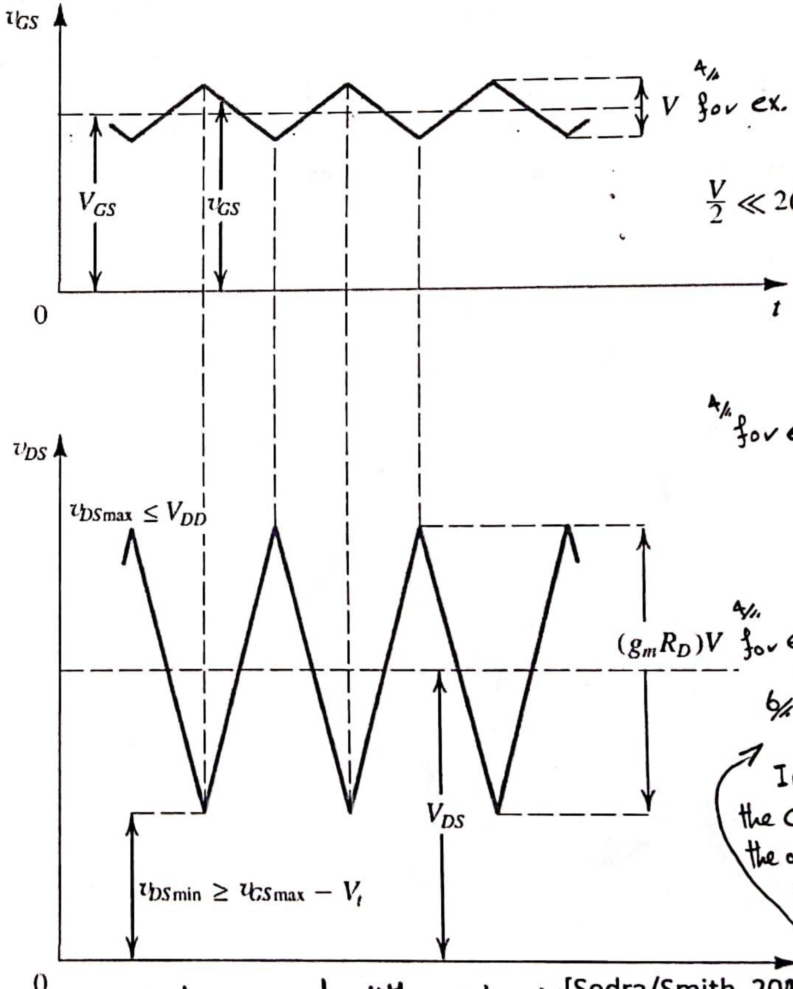
CS Amplifier Example

1. $A_v = G_m R_{out}$
$\simeq -g_m (R_D \| r_o)$
no degeneration
$\simeq -g_m R_D \rightarrow R_D \ll r_o$

2/ Important note to remember is that the signal is superimposed on a DC volt.
• In input: V_{GS}, • In output: V_{DS}

3/ Signal we suppose it's very small in the input but in the output it's an amplified signal. So, how we say that the small signal approx. is still valid while we have large signal @ the output?





4/ V for ex. 50mV

4/ for ex. $|A_v| = g_m R_D = 10$

4/ $(g_m R_D)V$ for ex. 500V

6/ I_D vs. V_{GS}
• We were interested to apply the small signal approx. on the I_D vs. V_{GS} characteristics which the ch. of the input side but ideally the output side has no effect on the current and the MOS.

5/ The answer is that we actually are interested with the small signal @ the input not the input as ideally the current of the transistor doesn't depend on "V_{DS}" it's VCCS (current source means that it's current doesn't depend on the applied voltage) so it's supposed that V_{DS} has no effect on the transistor.

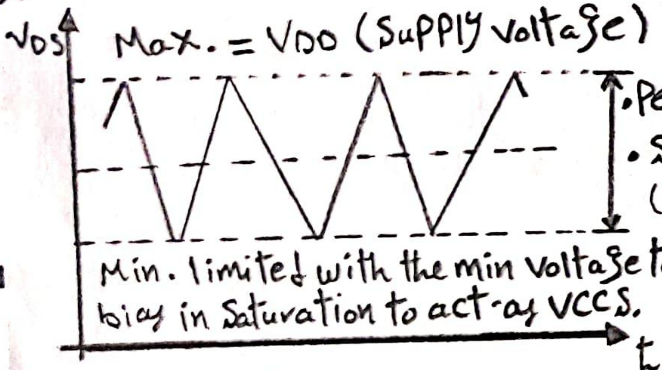
4/ If we consider 50mV as small signal we can't consider 500mV (0.5V) as small signal.

[Sedra/Smith, 2015]

7/ Does this mean that the output can change freely and amplifier won't be affected?

— off course No, There are limits, we'll Permit large signal variation @ the output with limits.

8/ What are the limitations of the output swing (the larger (Max.) and Min. values for the output)?



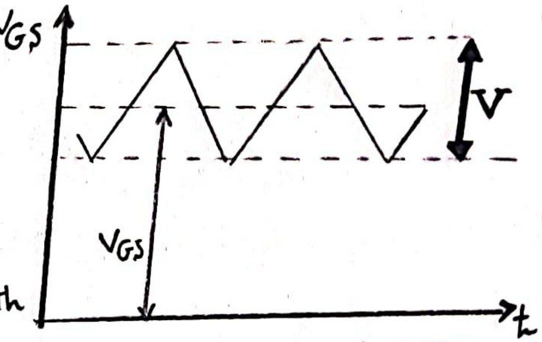
• Peak to Peak o/P swing

• Signal swing @ the o/P $(g_m R_D)V$

→ $V_{DS} > V_{ov}$

$V_{DS_{min}} \geq V_{GS\,max} - V_{th}$

$\therefore$ Max. Signal Swing = $V_{DD} - V_{ov}$



• we assume small signal @ the i/P what are the boundries?

• if for ex. 50mV how to know it's small or large signal?

① By analysis: substitute in the equation

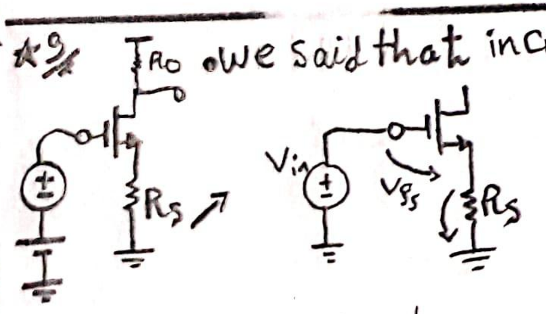
↳ ie. Solve the amplifier with the square law (non-linear model)

• Then it will result that the gain is non linear function then search for the condition at which this non-linear function can result linear gain by neglecting the non linear part and this analysis can be found in (Sedra-Smith)

★ The result in this case is the amplitude $\frac{V}{2} << 2(V_{GS}-V_t)$, $\frac{V}{2} << 2V_{ov}$

② By intuition: $\Delta V_{GS} << V_{ov}$ rough estimation

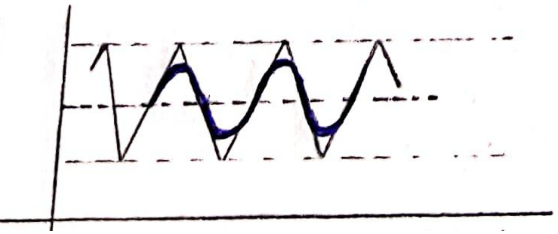
★9/ we said that increasing "Rs" linearize the amplifier but why? - as not all the Vin will be translated as Vgs ^.^ but some of Vin'll be a voltage drop on "Rs" So, the part be Vgs will result the non linearity and the other part 'll go to Rs, and by increasing Rs, smaller part will go to Vgs.

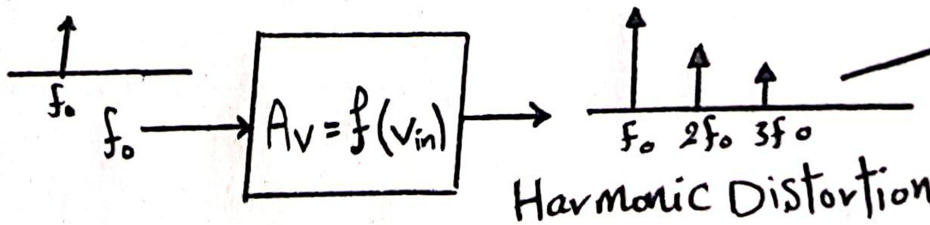


★ This non linearity is aresult that g_m is a function of Vin ($f(V_{in})$)

(or) $g_m = f(W/L, V_{ov})$ so by changing V_{gs} it changes g_m.

★ This non linearity is interpreted as: "Distortion"





→ fundamental + harmonics

Harmonic Distortion (HD)

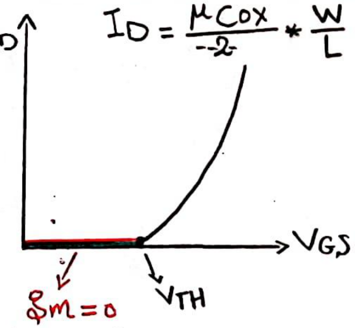
CS Large Signal Behavior "other Perspective from Razavi Book"

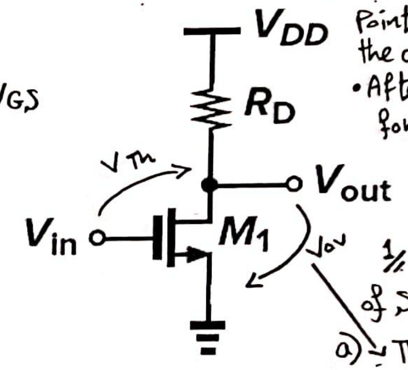
- Gain is non-linear:
  - 2/. $A_v = f(V_{in}) = -g_m . R_D$ ← slope
  - 3/. $g_m = f(V_{in})$
- For linear gain, A_v should NOT be $f(V_{in})$
- A_v and g_m are max at edge of triode
  - But they are highly non-linear
  - And the available signal swing vanishes

4/ $I_D = \frac{\mu C_{ox}}{2} * \frac{W}{L} V_{ov}^2 \xrightarrow{\frac{d}{dt} V_{GS}} \cdot g_m = \mu C_{ox} \frac{W}{L} V_{ov}$

↳ linear $V_{ov}\uparrow \therefore g_m \uparrow$ until reaching Point 'A' in ($g_m - V_{in}$) curve as @ Point A you'll leave Saturation and the above equation won't be valid.

• After 'A' you'll notice a degradation for 'g_m'

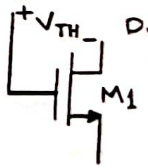




1/ You can know the edge of saturation by two ways:

a) This voltage "$V_{DS} = V_{ov}$"

b) or saying that there's channel @ the drain i.e. $V_{GD} = V_{Th}$

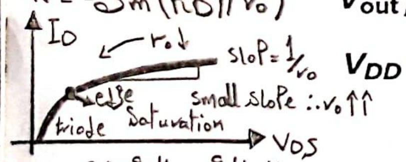


Drawing the gate connection taller than the Drain meaning that its voltage is higher.

7/ During the simulation you'll see a bit different results?

- As we ignored "r_o"

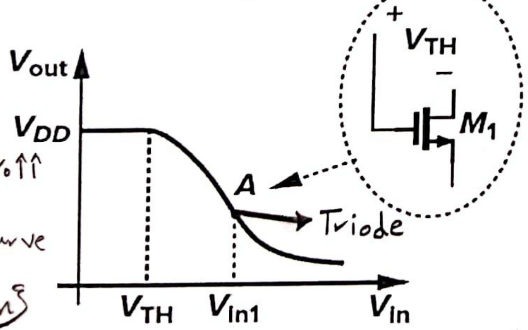
$A_v = -g_m (R_D // r_o)$

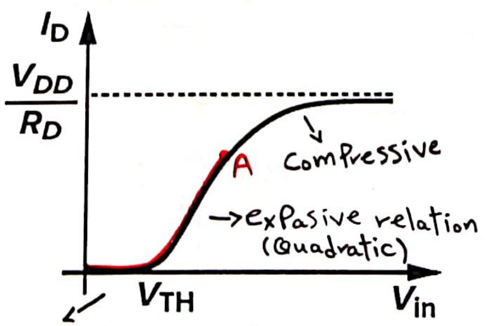


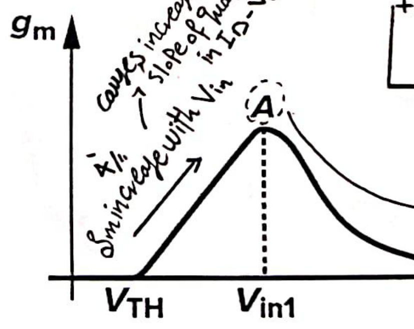
going through the curve this way

$\therefore$ the slope is increasing

$\therefore$ 'r_o' is decreasing







5/ Largest 'g_m' @ the edge of saturation

$\therefore$ Largest A_v

• But $V_{out} = V_{ov}$

$\therefore$ No available signal swing

6/ Till V_{th} the current almost equals zero then it'll increase "Quadratically" until it leaves the region of saturation then it'll compress until it reaches the largest possible value $\left(\frac{V_{DD}}{R_D}\right)$ and the reason for that is by increasing V_{in} then I_D increase and V_{out} is decreasing and ultimately the min. value for $V_{out} = 0$ @ which you'll get the largest current by ohm's law (V_{DD}/R_D).

• while going through the curve approaching the triode region → r_o is decreasing

$\therefore$ @ the edge of saturation r_o is small while going deeper into triode → Slope $\uparrow\uparrow$ → $r_o \downarrow\downarrow$ → $A_v \downarrow\downarrow$

★ The negative swing will set the MOS out of saturation.

Output Signal Swing

$$V_{out,max} = V_{DD} - V_{ov2}$$

$$V_{out,min} = V_{ov1} = V_{in,max} - V_{TH}$$

- Output swing $\approx V_{DD} - 2V_{ov}$ If $V_{ov_1} = V_{ov_2}$

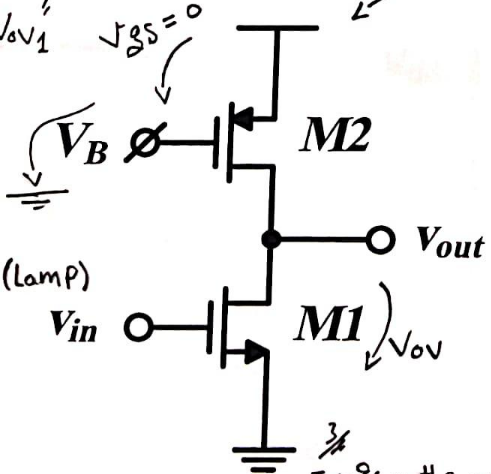
1/. The available Range:
- The chair height: V_{ov} for the MOS beneath "V_{ov_1}"
- The ceiling: is not V_{DD}, why?

-As we have above a MOS we want also to operate @ the saturation (current source) So, it's need to apply bias voltage on it "V_{ov_2}" (Lamp)

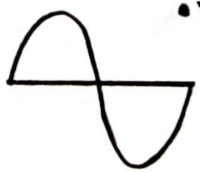
$\therefore$ The ceiling = $V_{DD} - V_{ov_2}$

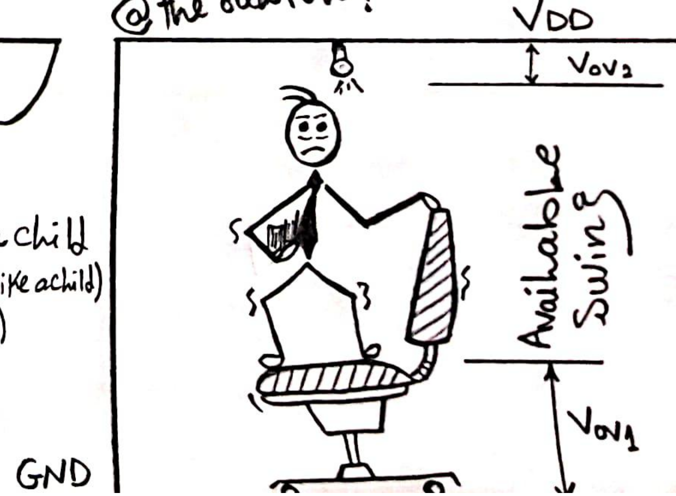
★1/. Same as the CS Amplifier But we replace "R_D" with active load.

$R_D = r_o$



★2/. With Large signal Perspective
- What's the available signal swing @ the output?





3/. Imagine the output as a child standing on a chair (Doesn't look like a child) (^.^)
- He can move or jump in a space Between the chair & the ceiling

CD Large Signal Behavior

- Why Source Follower?
  - Buffer
  - Level-shifter

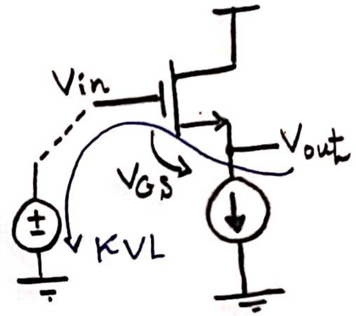
2/. In the Large Signal 'CD' has another use:

• used in Level Shifting

→ You told us that CD is a Source follower and $V_{out} = V_{in}$?

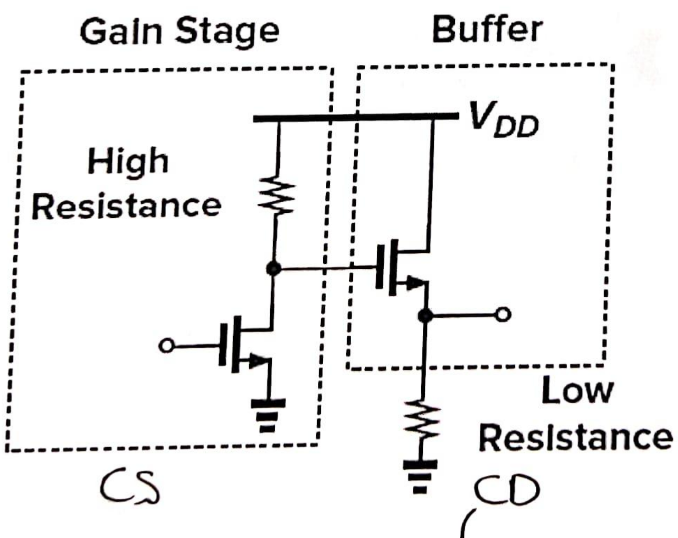
– It's right in small signal not in Large signal

★ In Large signal: Apply KVL to get V_{out}.

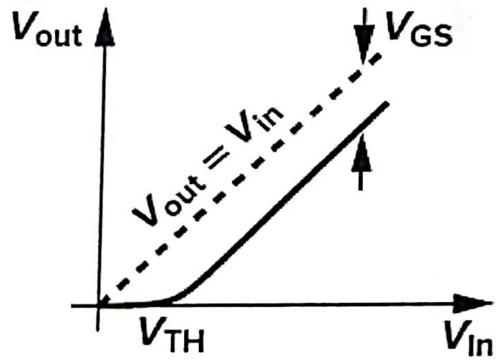


$\therefore V_{out} = V_{in} - V_{GS}$ → shift (Down Shifting)

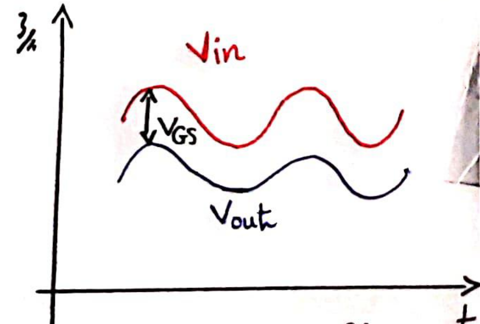
• as a result that V_{GS} is changing (unless I_D = Const.) this shifter won't be ideal i.e. some sort of error.



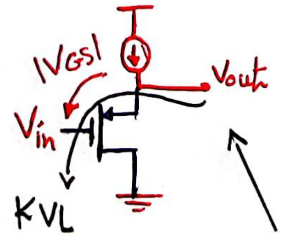
1/. act as a buffer with the gain stage



3/.



there is DC shift $= V_{GS}$



$V_{out} = |V_{GS}| + V_{in}$

for +ve shift

4/. This is −ve shifting

[Razavi, 2017]

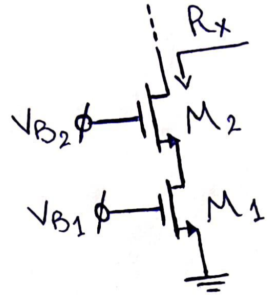
Thank you!

Dr. Hesham omran's Lecture
Fady Sabry Neam's notes

Quiz (1): lecture (6)

★ Quiz on: "Looking from Drain"

- Assume M_1 and M_2 have the same g_m and r_o, $g_m r_o \gg 1$, and neglect body effect
- Find R_x



Sol.

- for M_2:

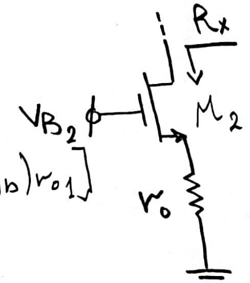
$\hookrightarrow R_{LFD_2} = r_o[1 + (g_m + g_{mb})R_{S_2}]$

$R_{S_2} = R_{LFD_1}$

- for M_1:

$\because R_S = 0$, $R_G = 0$ (i.e. Ac connected to the Gnd.)

$\therefore R_{LFD_1} = r_{o_1} = r_o$



$\therefore R_{LFD_2} = r_{o_2}[1 + (g_m + g_{mb})r_{o_1}]$

$\because g_m r_o \gg 1$

$\therefore R_{LFD_2} = r_{o_2}[(g_m + g_{mb})r_{o_1}] = g_m \cdot r_o^2$

neglect the Body effect

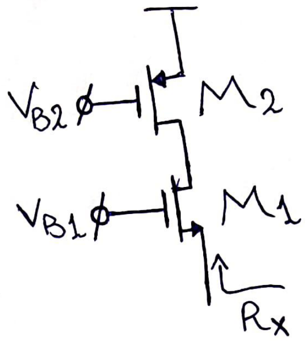
$\because r_{o_1} = r_{o_2}$

$\therefore R_x = g_m r_o^2$ #

Quiz (2): Lecture (6)

★ Quiz on: 'Looking from Source'

- Assume M_1 and M_2 have the same r_o, $g_m r_o >> 1$, and neglect body effect.
- Find R_X



Sol.

for M_1:

$\to R_X = R_{LFS_1}$

$$R_{LFS_1} = \frac{1}{g_m + g_{mb}}\left(1 + \frac{R_{D_1}}{r_o}\right)$$

- $R_{D_1} = R_{LFD_2}$

for M_2:

$$\to R_{LFD_2} = r_o\left[1 + (g_m + \cancel{g_{mb}})R_{S_2}\right]$$

$$R_{S_2} = 0$$

★ Active Load: as the Gate & the Source are AC short circuit

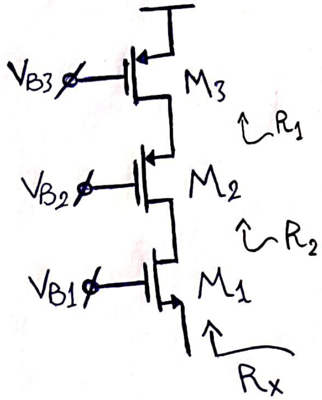
$$\therefore R_X = \frac{1}{g_m + \cancel{g_{mb}}}\left(1 + \frac{r_o}{r_o}\right)$$

neglect body effect

$$\therefore R_X = \frac{2}{g_m} \quad \#$$

Quiz (3): Lecture (6)

- Assume M_1, M_2, and M_3 have the same g_m and r_o, $g_m r_o \gg 1$, and neglect body effect
- Find R_x



Sol.

- for M_3:

$\longrightarrow R_1 = R_{LFD} \rightarrow$ (active load)

$\therefore R_1 = r_o$

- for M_2:

$\longrightarrow R_2 = R_{LFD} = r_o\left(1 + (g_m + \cancel{g_{mb}}) R_S\right)$

neglect body effect

$\therefore R_2 = r_o(1 + g_m r_o)$

$\because g_m r_o \gg 1$

$\therefore R_2 = g_m r_o^2$

- for M_1:

$\longrightarrow R_X = R_{LFS} = \dfrac{1}{g_m + g_{mb}}\left(1 + \dfrac{R_{D_1}}{r_o}\right)$

$\because \underline{R_{D_1}} = \underline{g_m r_o^{\cancel{2}}}$

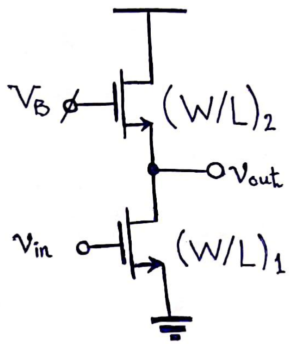
$\quad\; r_o \qquad \cancel{r_o}$

$\therefore R_x = \dfrac{1}{g_m}(1 + g_m r_o) = \dfrac{1}{g_m}(g_m r_o) = r_o$ #

Quiz (4): Lecture (6)

* Quiz on: "Common Source Amplifier"

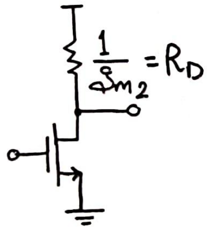
- The Circuit below shows a CS amplifier with diode-connected load
- Find the gain using $G_m R_{out}$ (ignore body effect and CLM).
  - Express the gain in terms of $(W/L)_1$ and $(W/L)_2$.
- This is a "Linear" CS amplifier.



Sol.

$$A_v = G_m R_{out}$$

- first for M_2 when dectivating V_B
  → Gate & Drain are connected
  So, Diode connected



$$G_m = \frac{-g_m}{1 + \cancel{g_m R_S}}$$

$R_S = 0$

$$\therefore G_m = -g_{m1}$$

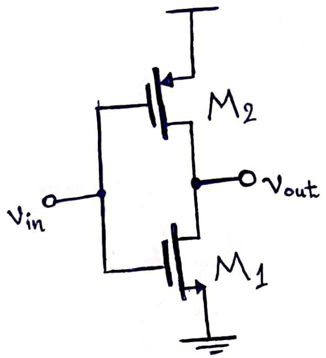
$$R_{out} = \frac{1}{g_{m2}} \parallel r_o \simeq \frac{1}{g_{m2}}$$

$$A_v = -\frac{g_{m1}}{g_{m2}} = -\frac{\sqrt{\mu_n C_{ox} \left(\frac{W}{L}\right)_2 2 I_D}}{\sqrt{\mu_n C_{ox} \left(\frac{W}{L}\right)_2 2 I_D}}$$

$$\therefore A_v = -\sqrt{\frac{(W/L)_1}{(W/L)_2}} \quad \#$$

Quiz(5): Lectur(6)

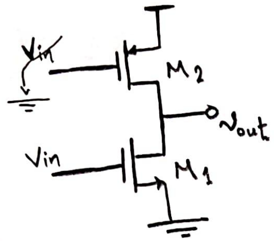
- The Circuit below Shows a complementary CS amplifier (inveter amP).
- Find the gain using $G_m R_{out}$.



Sol.

• By applying SuperPosition theorem :

① Dectivate Vin for M_2



$$A'_v(\text{for } M_1) = G'_m R'_{out}$$

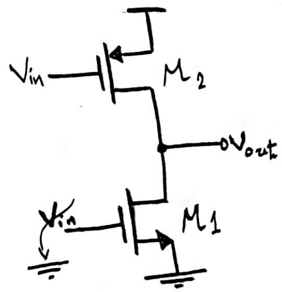
$$G'_m = \frac{-g_{m_1}}{(1+\cancel{(g_{m_1}+g_{mb_1})R_{S_1}})} \quad (\cancel{\ldots} \to 0)$$

$$= -g_{m_1}$$

$\therefore A'_v(\text{for } M_1) = -g_{m_1} * R'_{out}$, $R'_{out} = r_{o1} \parallel r_{o2}$

$$A'_v = -g_{m_1}(r_{o1} \parallel r_{o2})$$

② Deactivate Vin for M_1



$$A''_v(\text{for } M_2) = G''_m R''_{out}$$

$$G''_m = \frac{-g_{m2}}{(1+\cancel{(g_{m2}+g_{mb2})R_{S_2}})} \quad (\cancel{\ldots} \to 0)$$

$$= -g_{m2}$$

$\because R''_{out} = r_{o1} \parallel r_{o2}$

$$\therefore A''_v = -g_m(r_{o1} \parallel r_{o2})$$

Sum ① & ②

$$\therefore A_v = -(g_{m1} + g_{m2})(r_{o1} \parallel r_{o2})$$

وَمَا أُوتِيتُمْ مِنَ الْعِلْمِ إِلَّا قَلِيلًا

Allah almighty said in the Qur'an :
"and you ⌜O humanity⌝ have been given but little knowledge."

لو أن الناس كلما استصعبوا أمرًا تركوه ما قام للناس دنيا ولا دين

The Muslim Caliph Umar ibn Abdulaziz, May Allah have mercy on him, Said:
"If every time people found something difficult, they abandoned it, then neither worldly affairs nor religion would have ever been established for people."

- All Credits for these lectures go to **Dr. Hesham Omran**, Associate Professor at Ain Shams University and CTO at Master Micro, May Allah bless Dr. Hesham for these Lectures.

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