ELEC 404

MOS Transistor Review

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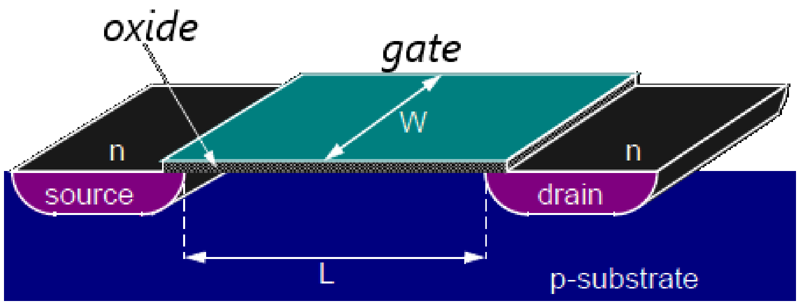
HWO

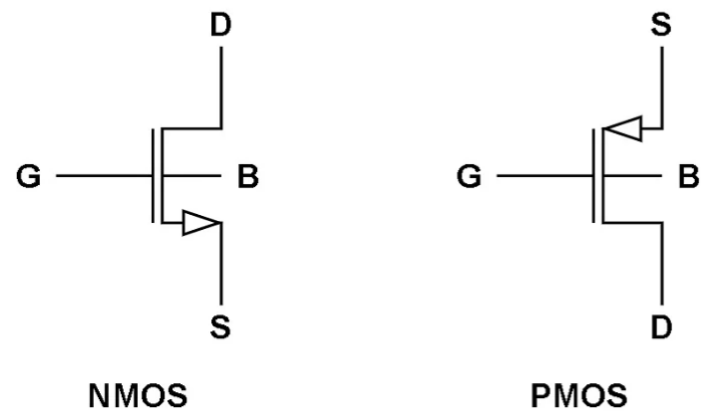
Problem 1:

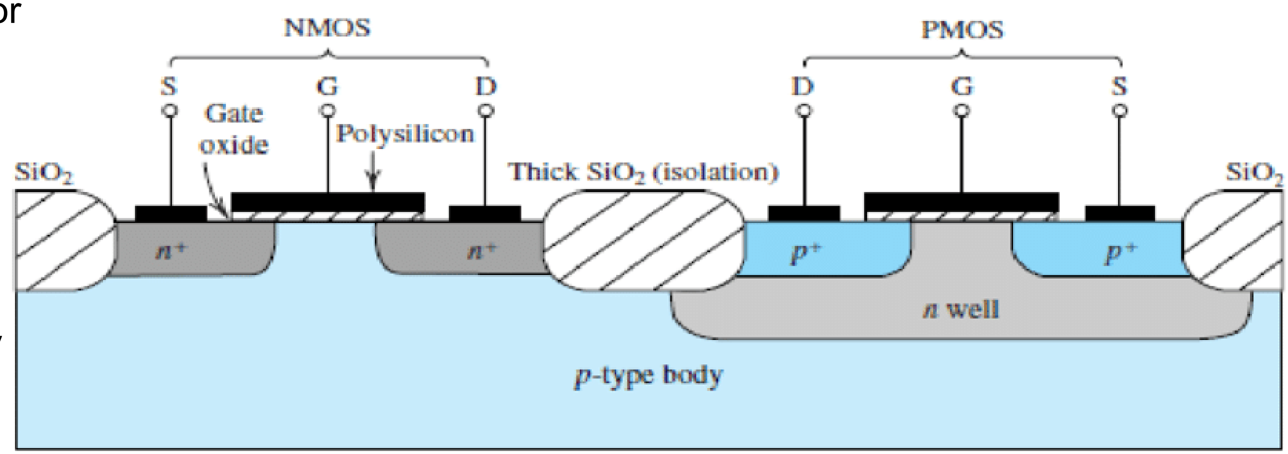
NMOS: ON→ VGS ≥ Vth; Saturation → VDS ≥ VGS-Vth

PMOS: ON→ VSG ≥ $|Vth|$; Saturation → VSD ≥ VSG- $|Vth|$



Planar NMOS transistor





CMOS Technology

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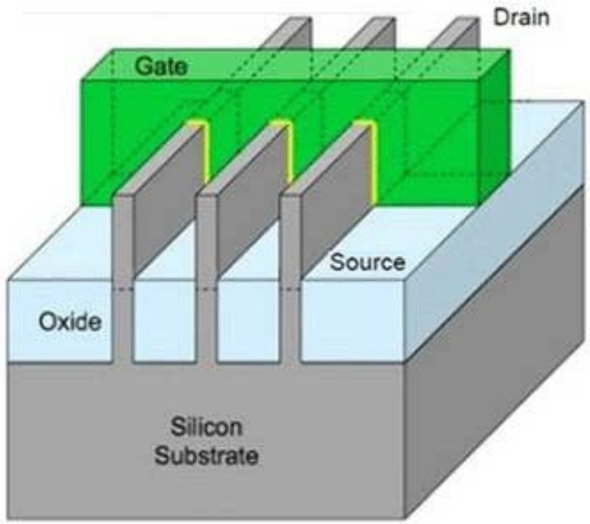
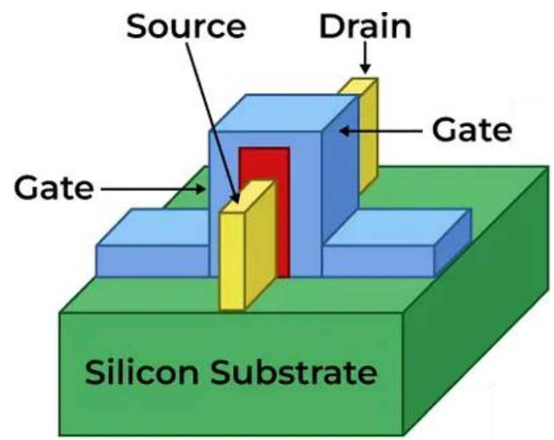
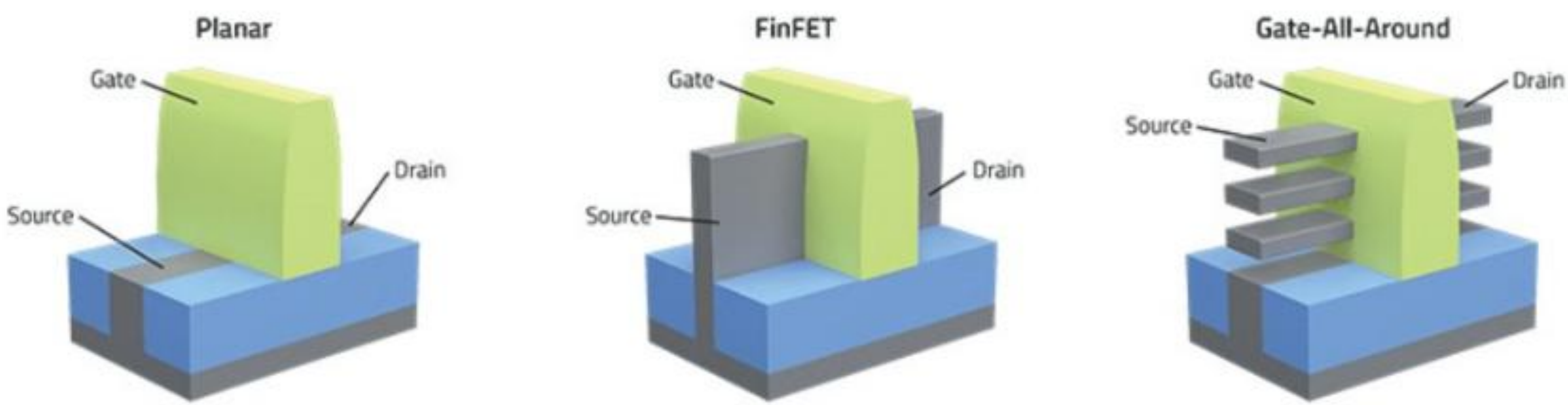
Problem 1:





FinFet Transistor



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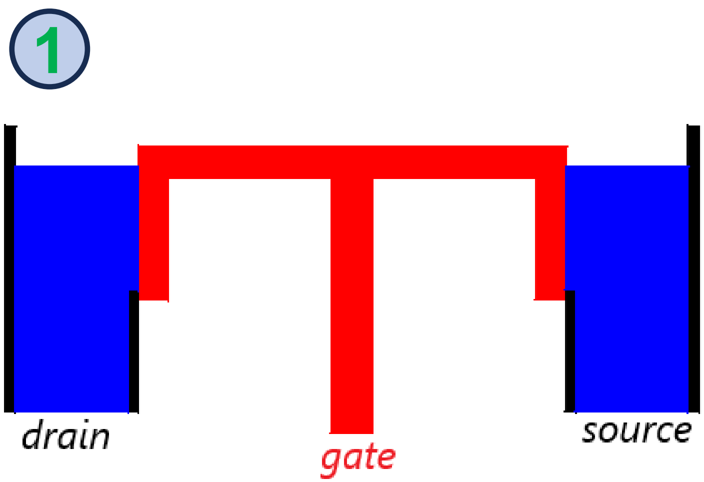
Problem 1:

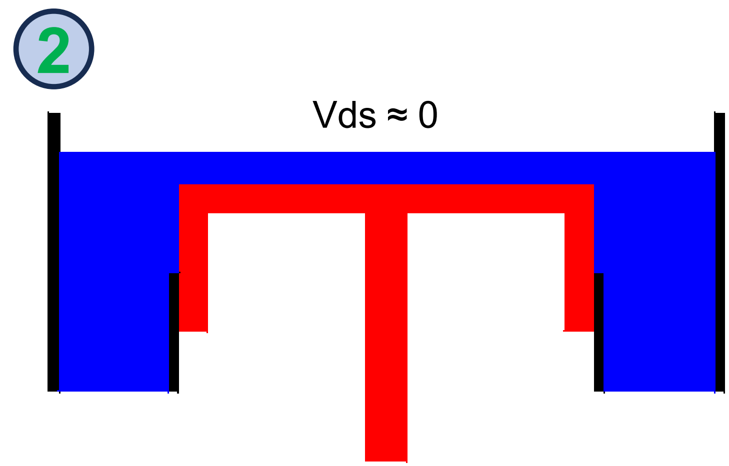
Simple model (water reservoirs and valve) for understanding the regions of operation:



Vgate < Vch
drain and source completely disconnected

OFF

No conduction
No current



Vds is very small, deep linear region

ON

Vgate > Vch
Vdrain ≈ Vsource

There is conduction (like an ON switch)
But no current

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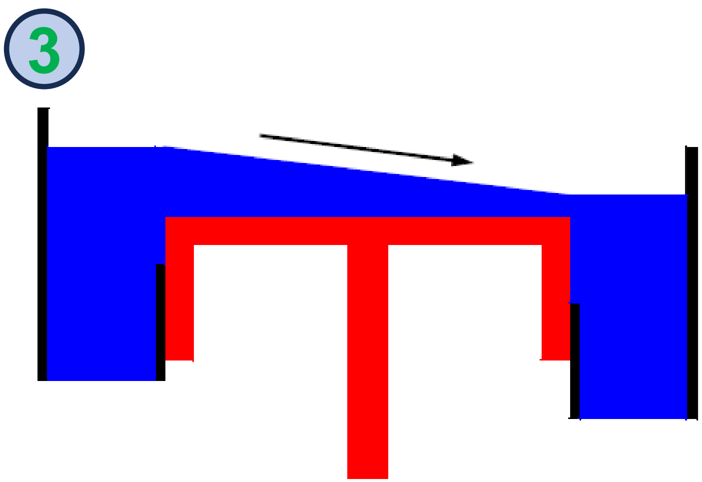
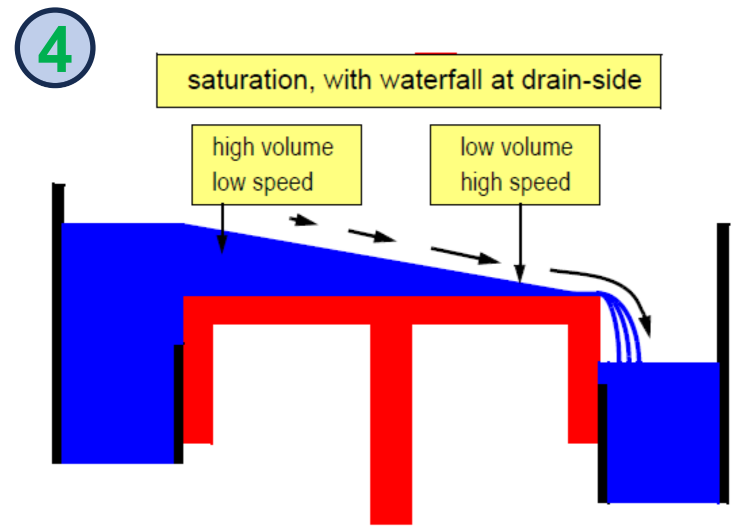
Problem 1:

Simple model (water reservoirs and valve) for understanding the regions of operation:



vgate > Vch
Vdrain > Vsource
Vds< Vgs - Vth
in Triode region

The flow strongly depends on drain-source potential



Vgate > Vth
Vds > Vgs -Vth

Doesn’t matter how high is the drain potential (water)
The flow depends on the width length and gate voltage level.
The current is independent of Vds

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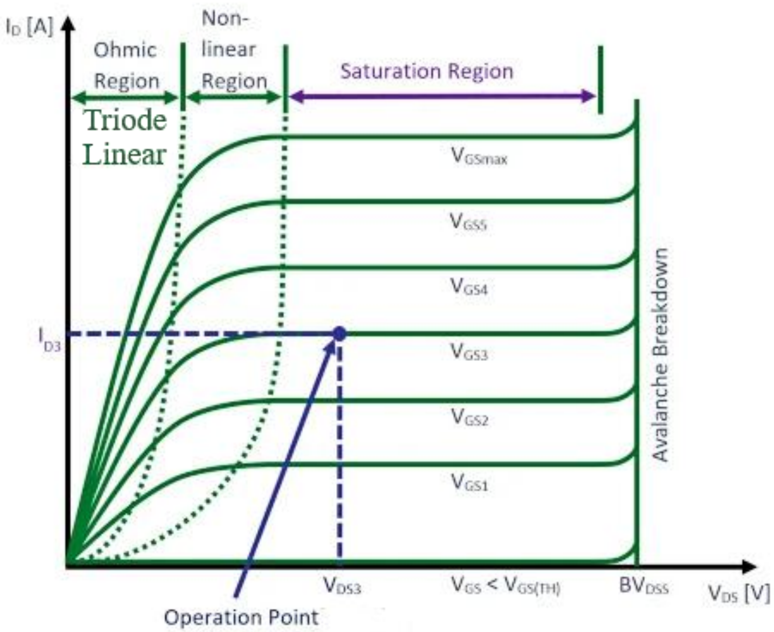
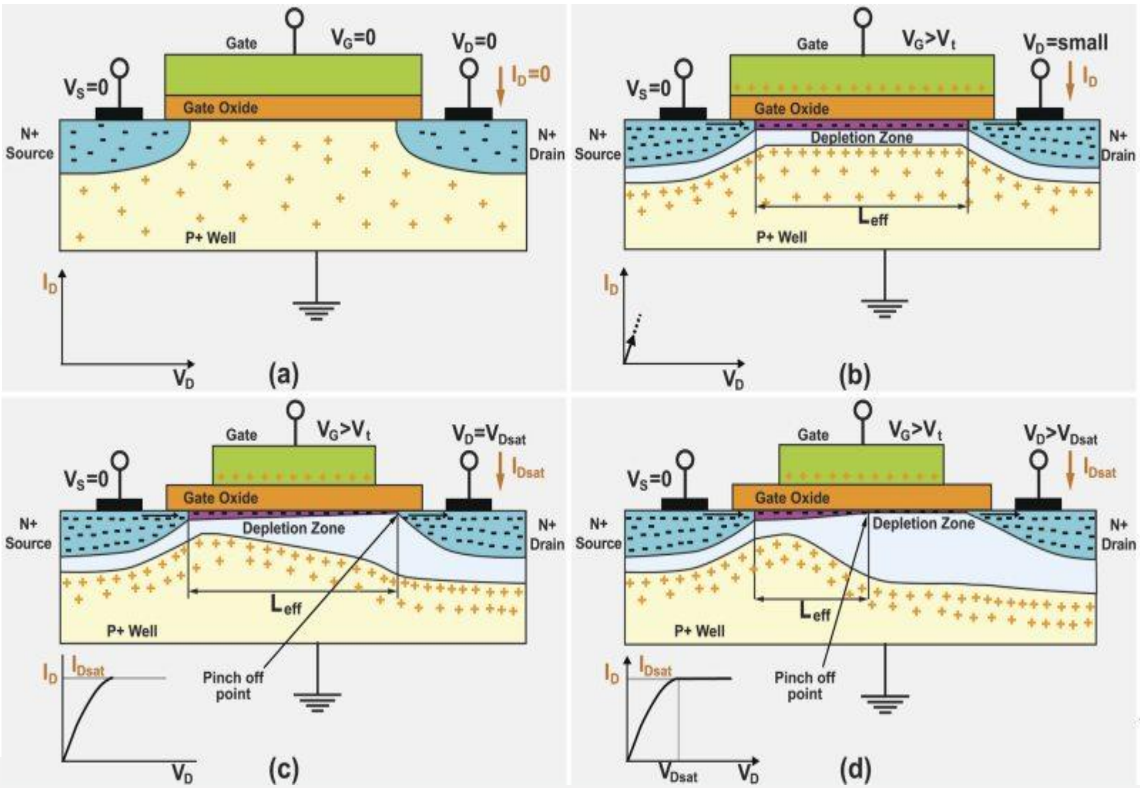
Problem 1:

$$I_D = \mu_n C_{ox} \frac{W}{L} \left[(V_{GS} - V_{TH}) V_{DS} - \frac{V_{DS}^2}{2} \right] \quad \text{Triode region}$$

$$I_D = \frac{1}{2} \mu_n C_{ox} \frac{W}{L} (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS}) \quad \text{Saturation region}$$





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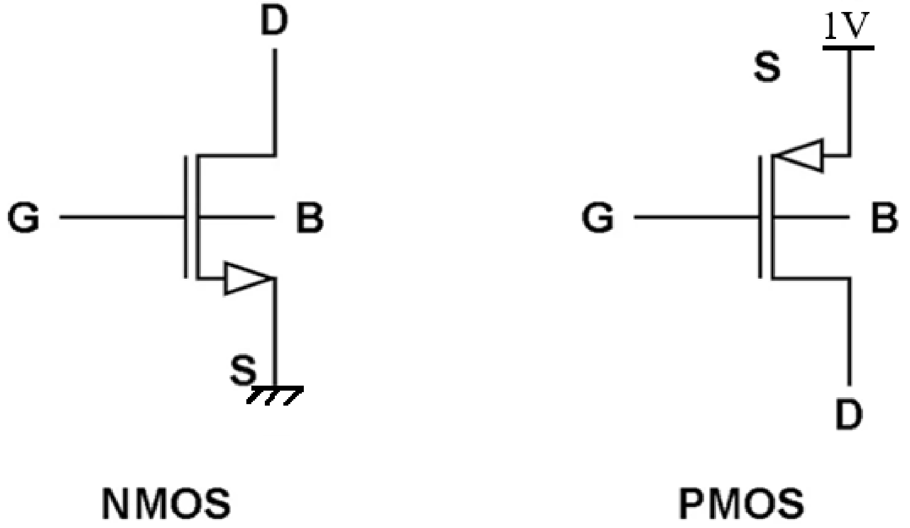
Problem 1:

VG	VD	Mn region	Mp region
0.7	1	Sat.	Off
0.7	0.7	Sat.	Off
0.7	0.6	Sat.	Off
0.2	0.8	Off	Triode
0.5	0.1	Triode	Sat.



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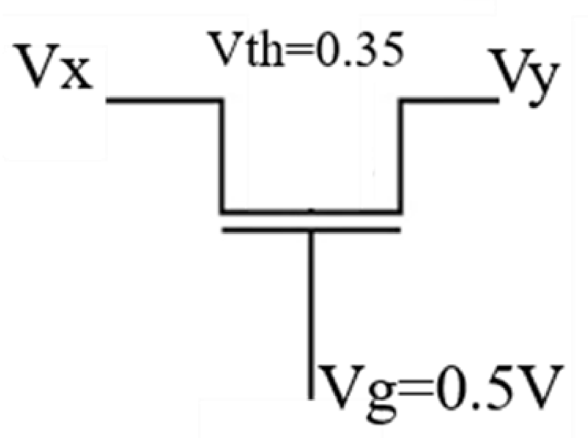
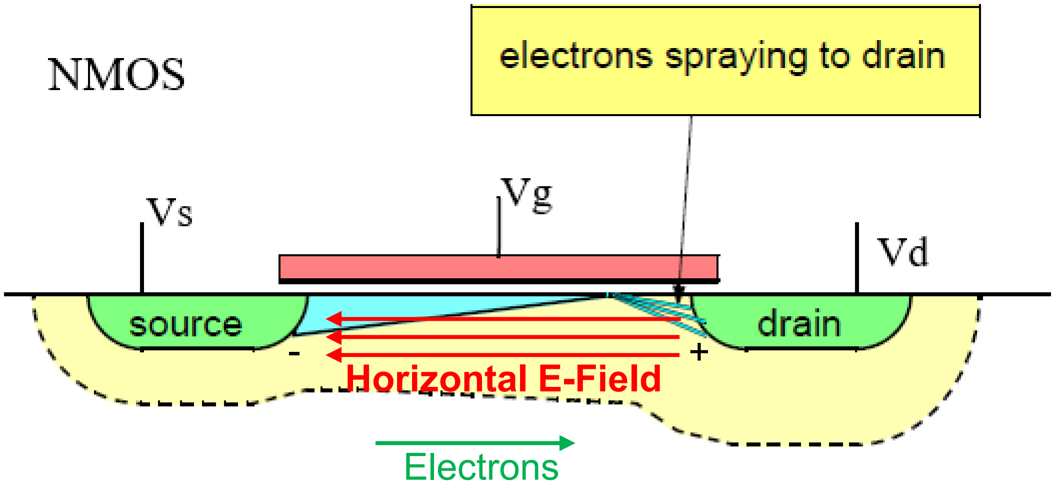
Problem 2:

In NMOS → Drain: most positive node

In PMOS → Source: most positive node





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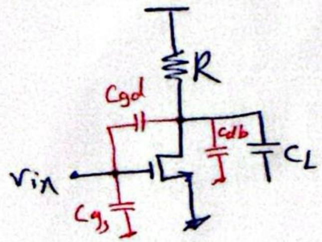
Problem 3:

3)

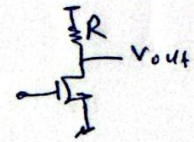


CS-gain stage $\begin{cases} r_o \to \infty \\ g_{mb} \to 0 \end{cases}$

assuming v_{in} as an ideal ac source

$C_{gs} \to$ ~~short~~ no effect

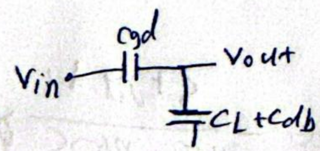
Low freq $\Rightarrow$ capacitors are open



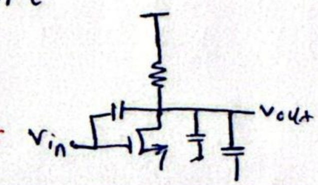
$A_v = -g_m R$

very high freq $(\omega \to 0) \Rightarrow$ capacitors are short

$$\frac{V_{out}}{v_{in}} = \frac{C_{gd}}{C_{gd}+C_L+C_{db}} \simeq 0 \Leftarrow$$



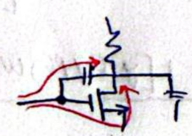
$\Leftarrow$



Mid-freq:

$$A_v(s) = R\,\frac{sC_{gd} - g_m}{1 + RC_t s} \qquad C_t = C_L + C_{gd} + C_{db}$$

$\omega_p = -1/RC_t$ $\qquad \omega_z = +g_m/C_{gd}$ (RHP): feedforward path



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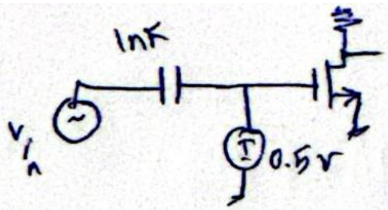
Problem 4:

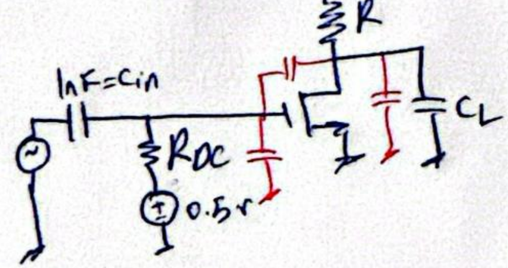
4)



DC source will short ac input to ground

$$\frac{V_{out}}{V_{in}} = 0$$

solution



$$\frac{V_{out}(s)}{V_{in}(s)} = \frac{C_{in} R_{DC} R s (C_{gd} s - g_m)}{1 + s[R_{DC}(C_{in}+C_{gs}+C_{gd}) + R(C_{gd}+C_L+C_{db}) + g_m C_{gd} R_{DC} R] + s^2 R_{DC} R[(C_L+C_{db})(C_{in}+C_{gs}+C_{gd}) + C_{gd}(C_{in}+C_{gs})]}$$

if $R_{DC} C_{in} \gg \omega_{desired} > 1 \cdot \omega_{desired}$

$$\frac{V_{out}(s)}{V_{in}(s)} = R \frac{sC_{gd} - g_m}{1 + RC + s} \Rightarrow \text{the same.}$$

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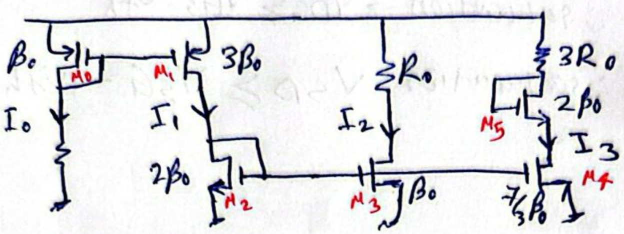
Problem 5:

5)



$I_1 = \frac{3\beta_0}{\beta_0} I_0 = 3I_0$; $I_2 = \frac{\beta_0}{2\beta_0} I_1 = \frac{1}{2} \times 3I_0 = \frac{3}{2} I_0$

$I_3 = \frac{7}{6} I_1 = \frac{7}{2} I_0$

All transistors should be in saturation for trans with I_0 & $\beta_0 \rightarrow V_{gs} = V_{od_0} + V_{th}$

M_0: saturation $\Rightarrow V_{od_0} = \sqrt{\frac{2I_0}{\beta_0}} \Rightarrow V_{gs_0} = V_{od_0} + |V_{th}|$

M_1 & M_2 : saturation.

$M_2 \rightarrow V_{gs_2} = V_{th} + \sqrt{\frac{3}{2}} V_{od_0}$

for M_3 to be in saturation $\rightarrow V_{dd} - R_0 \times 1.5 I_0 > \sqrt{\frac{3}{2}} V_{od_0}$

$\Rightarrow (1) \Rightarrow R_0 < \frac{2(V_{dd} - \sqrt{\frac{3}{2}} V_{od_0})}{3I_0}$

for M_4 to be in saturation $\rightarrow V_{dd} - \frac{21}{2} R_0 I_0 - \underbrace{(\sqrt{\frac{7}{4}} V_{od_0} + V_{th})}_{V_{gs_5}} > \sqrt{\frac{3}{2}} V_{od_0}$

$\rightarrow (2) \Rightarrow R_0 < \frac{2}{21 I_0} (V_{dd} - V_{gs_5} - \sqrt{\frac{3}{2}} V_{od_0})$

$\rightarrow$ sets the maximum of R_0 $\Rightarrow$ to make all tran in saturatio

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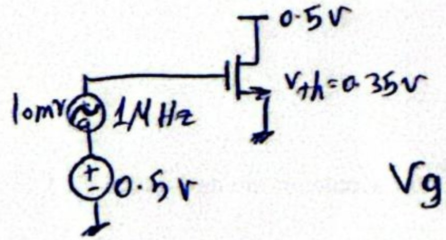
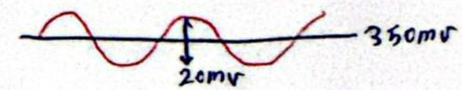
Problem 6:

6) →

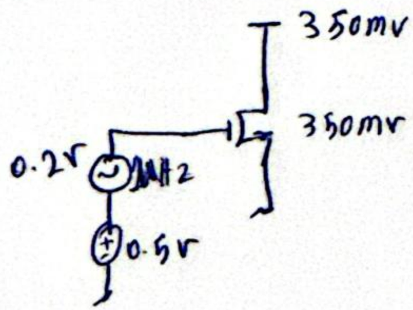


Vdc-gate ⇒

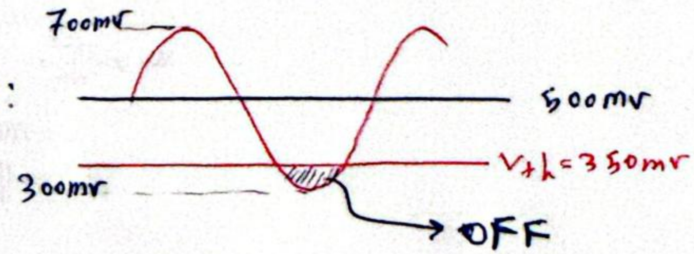


$V_{gs} \rightarrow$ always $> V_{th}$ ON

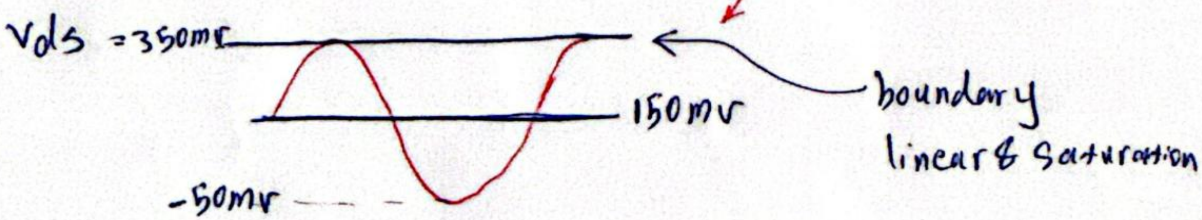
$V_{ds} = 0.5V > V_{gs} - V_{th}$ ✓ saturation



Vgate :
$= V_{gs}$



$V_{ds} = 350mV > \underline{V_{gs} - 350mV}$



when ON → saturation.

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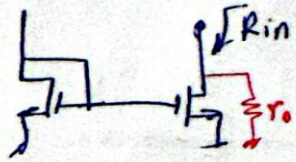
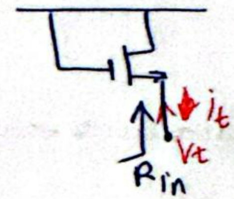
Problem 7&8:

7)



$R_{in} = r_o$

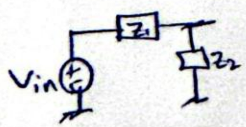


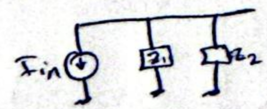
$i_t = -i_d = -g_m(-v_t) = g_m v_t$

$R_{in} = \frac{v_t}{i_t} = 1/g_m$

$R_{in} = 1/g_m \,||\, r_o$

8)





V_{Z_1}	$V_{in}\frac{Z_1}{Z_1+Z_2}$	$I_{in}\frac{Z_1 Z_2}{Z_1+Z_2}$
V_{Z_2}	$V_{in}\frac{Z_2}{Z_1+Z_2}$	″ ″
I_{Z_1}	$\frac{V_{in}}{Z_1+Z_2}$	$I_{in}\frac{Z_2}{Z_1+Z_2}$
I_{Z_2}	$\frac{V_{in}}{Z_1+Z_2}$	$I_{in}\frac{Z_1}{Z_1+Z_2}$

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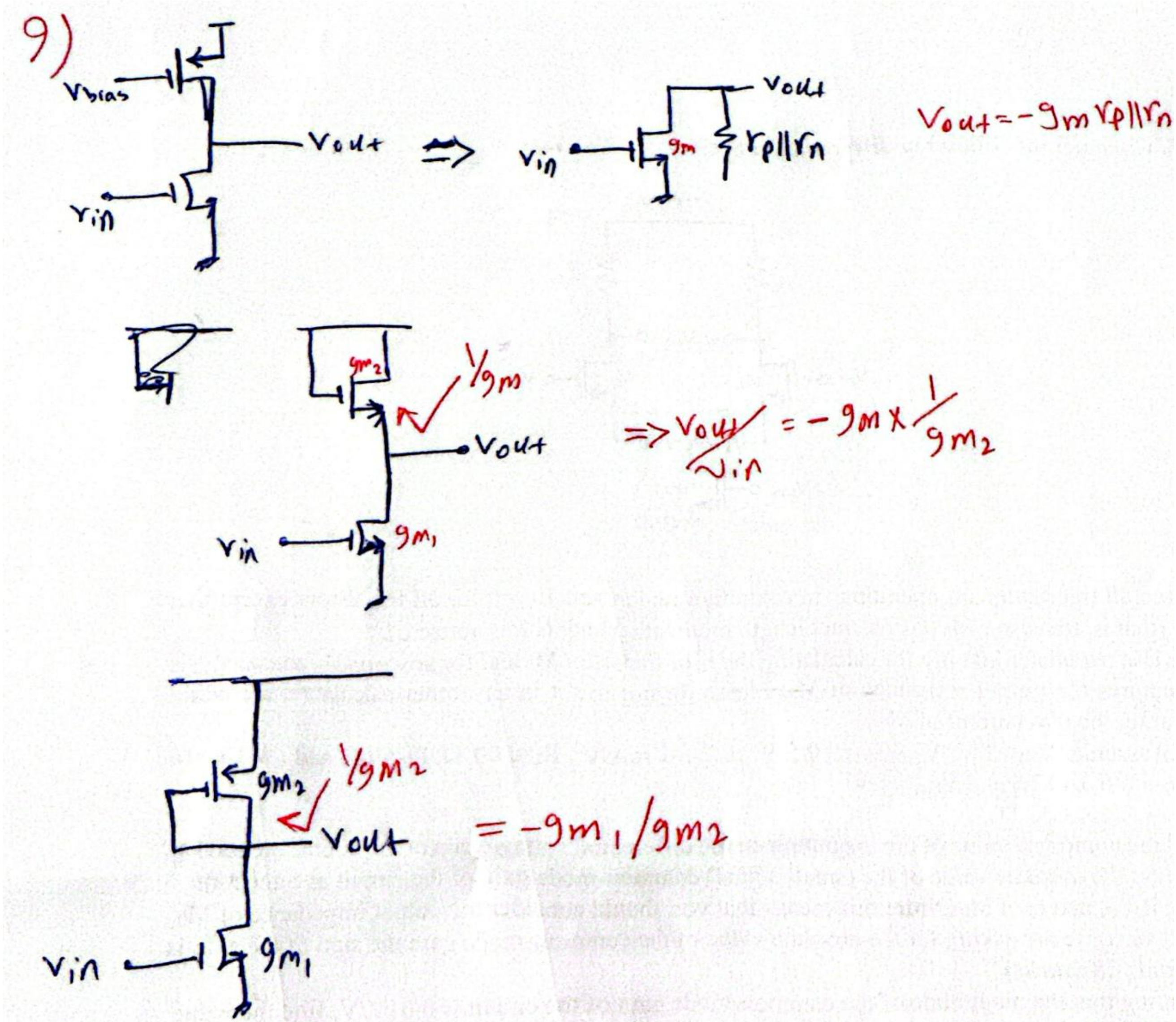
Problem 9:



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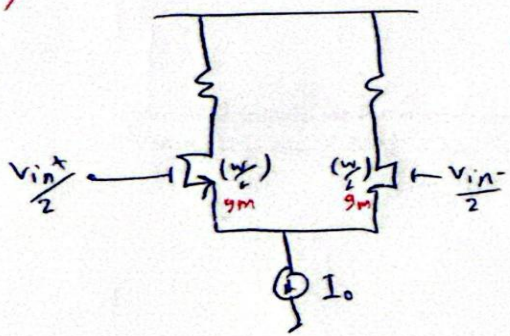
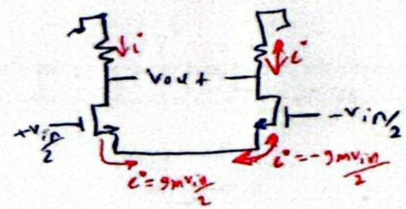
Problem 10:

10)



diff mode



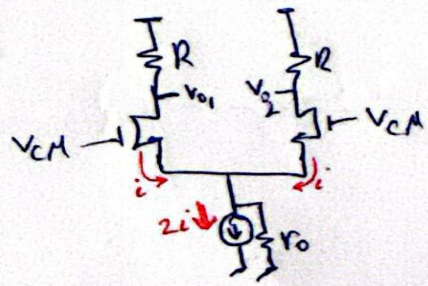
$$V_{out} = g_m \frac{v_{in}}{2} R - \frac{g_m v_{in} R}{2} = -g_m R V_{in}$$

$$A_d \Rightarrow \frac{v_{out}}{v_{in}} = -g_m R$$

comm mode $\Rightarrow$ assuming fully differential output $A_{CM} = 0$

assuming single-ended output

$A_{CM} \Rightarrow$



$$V_{o1} = -R i$$

$$V_{CM} = i g_m^{-1} + 2 i r_o$$

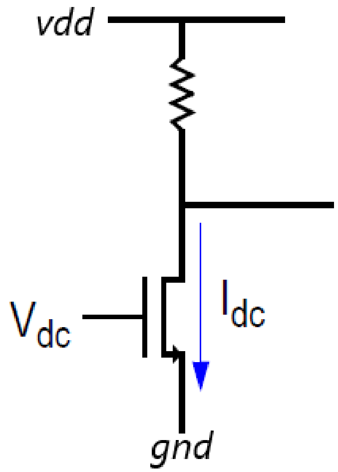
$$i = \frac{V_{CM}}{2r_o + 1/g_m}$$

$$V_{o1} \Rightarrow V_{o2} = -\frac{R}{1/g_m + 2r_o} \simeq \frac{-R}{2r_o} = A_{CM}$$

$$CMRR = \frac{A_d}{A_{CM}} = \frac{-g_m R}{-R/2r_o} = 2 g_m r_o$$

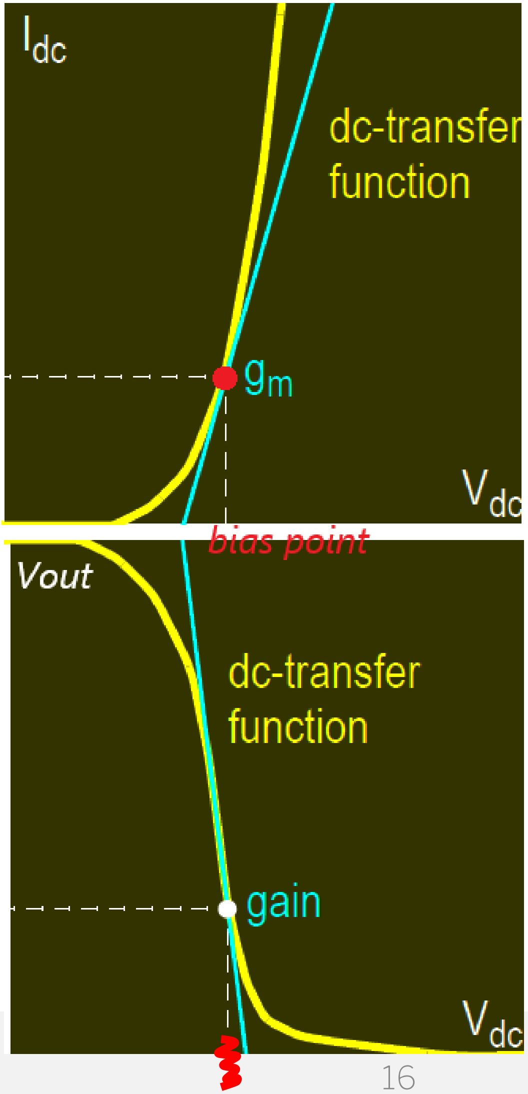
DC Bias Point

Purpose: setting the transistors region and bias point for getting specific dc, transient and ac behavior.



Finds the steady-state (time-invariant) solution to the bias point of each node.

- Sets all capacitors as open circuits and inductors as short circuits.
- Solves nonlinear equations to find DC voltages and currents at every node and device.
- DC analysis is a pre-requisite for any other analysis/simulation.



Use cases:

- Checking bias voltages/currents.
- Verifying transistor regions (saturation, triode, etc.).
- Initial condition for other simulations.

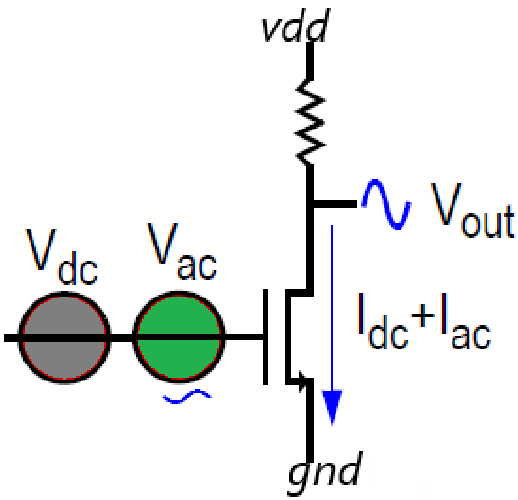
AC Analysis

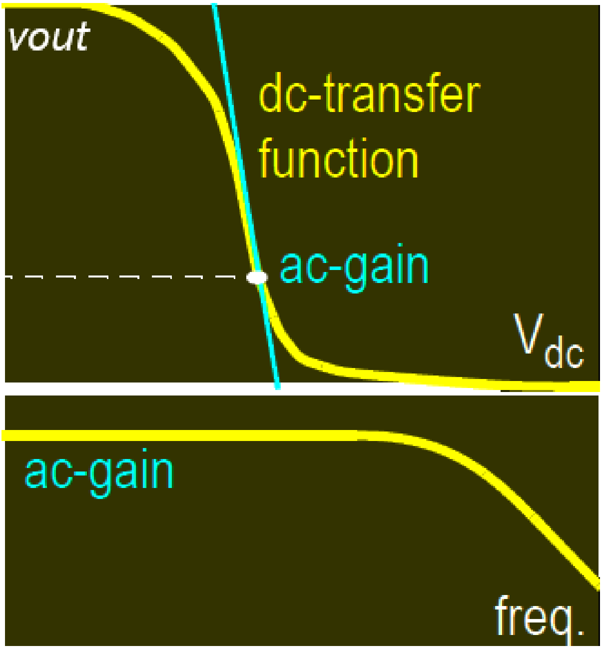
Purpose: Analyzes how the circuit responds to infinity small sinusoidal signals at different frequencies.
Can only be done after a correct biasing (dc).

- Linearizes the circuit around the DC operating point.
- Sweeps frequency (e.g., 1 Hz to 10 GHz) and computes gain, phase, impedance, Bode plots.

Use cases:

- Frequency response of amplifiers.
- Phase margin and gain margin.
- Impedance analysis.

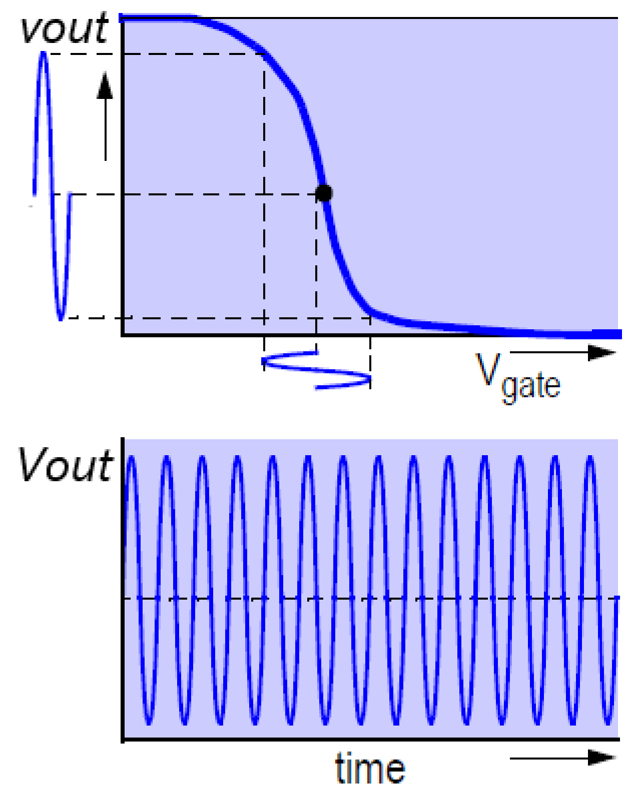




Transient Analysis

Purpose: Simulates time-dependent behavior; how voltages and currents evolve over time. Transient Analysis is the most important (reliable) analysis.

- Transient-analysis looks at everything.
- Solves nonlinear differential equations step-by-step over time.
- Captures switching, oscillation, and any non-linear dynamic behavior.



Use cases: always

- Oscillator startup, ringing, delay, and transient response, time-domain noise or distortion.

The circuit may function correctly in DC, AC and PSS simulations but if the transient response is weird, the circuit will not perform as expected in real case.

Always make sure that the transient simulation is correct.

Cadence Spectre / SpectreRF Analyses Summary

Analysis	Type / Domain	Main Purpose	Typical Use Case
dc	Static	Find DC operating point	Bias voltages, currents
ac	Small-signal (Frequency)	Linear frequency response	Gain, bandwidth, phase margin
tran	Time-domain (Nonlinear)	Waveform over time	Startup, switching, transient
noise	Small-signal (Frequency)	Device noise analysis	Amplifiers, filters
pss	Periodic Steady-State	Find periodic operating point	Oscillators, mixers
pnoise	Periodic Noise	Compute phase noise, sidebands	Oscillators, synthesizers
pac	Periodic AC	Small-signal freq. response	Conversion gain in mixers
pxf	Periodic Transfer	Input–output transfer	Injection pulling, gain
psp	Periodic S-Params	S-parameters under PSS	Nonlinear RF block analysis
qpss	Quasi-Periodic Steady-State	Multi-tone steady-state	Mixers, modulators
qpnoise	Quasi-Periodic Noise	Noise in multi-tone systems	Multi-tone RF analysis
qpac / qpxf	Quasi-Periodic AC / Transfer	Small-signal around QPSS	Multi-tone mixers
hb	Harmonic Balance	Large-signal frequency-domain	Power amps, mixers
hbnoise	HB Noise	Noise in HB domain	Oscillators, RF amps
hbsp / hbxf	HB S-Params / Transfer	Transfer in HB domain	RF power systems
stb	Stability (Linear)	Loop gain & phase margin	Feedback, PLLs
hbstb	Stability (HB / PSS)	Loop gain under periodic op.	RF feedback, PLLs
sp	S-Parameter (Linear)	Network characterization	Filters, matching networks
xf	Transfer Function	Linearized node transfer	Impedance, noise figure
pz	Pole-Zero	Find poles and zeros	Stability, transient insight
lf	Large-Signal Frequency	Frequency sweep (nonlinear)	Power compression, sweep
sens	Sensitivity	Variation sensitivity	Design margin, yield
dcmatch	Mismatch (DC)	DC mismatch due to variations	Offset voltage
acmatch	Mismatch (AC)	AC mismatch in response	Gain/phase mismatch
envlp	Envelope	Envelope of modulated signal	Communication circuits
of / ofa	Oscillation Frequency	Finds oscillation freq.	Free-running oscillators

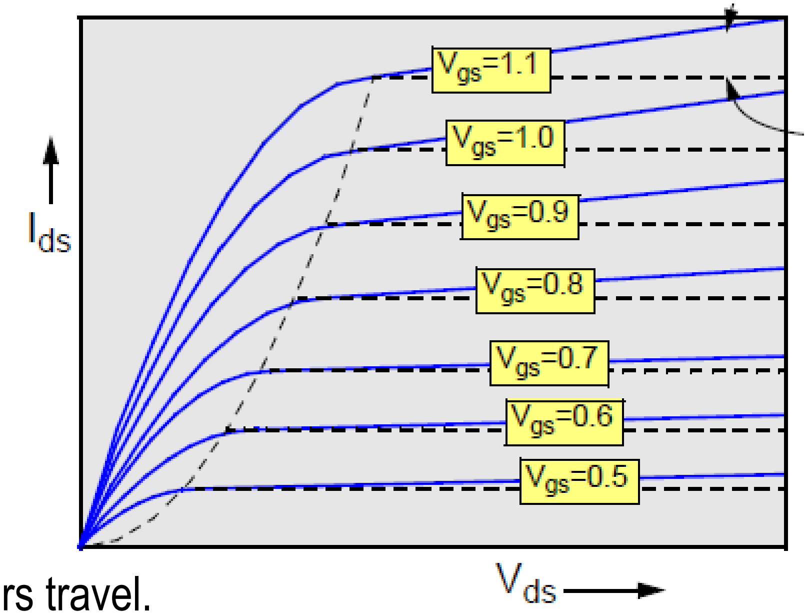
2^{nd} order effects

2^{nd} order effects:

- Body effect: modulating threshold voltage.
- Channel length modulation:

$$I_d = \frac{W}{2L}\mu C_{ox}(V_{gs} - V_t)^2(1 + \boxed{\lambda}.V_{ds})$$

$$r_o = \frac{dVds}{dId} = \frac{1}{\lambda Id}$$

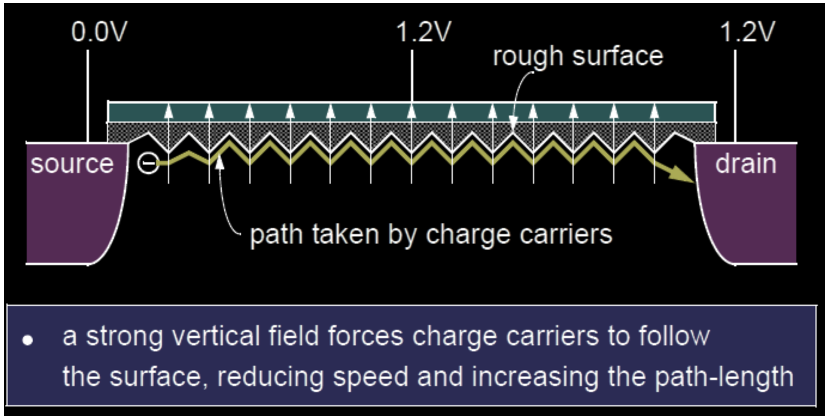


- Mobility reduction:

→ Reduce carrier speed & increase the distance carriers travel.

$$I_d = \frac{W}{2L}\frac{\mu_o}{(1 + \theta(V_{gs}-V_t))}C_{ox}(V_{gs} - V_t)^2$$

- with $\theta = 0.05 - 0.25\ [V^{-1}]$

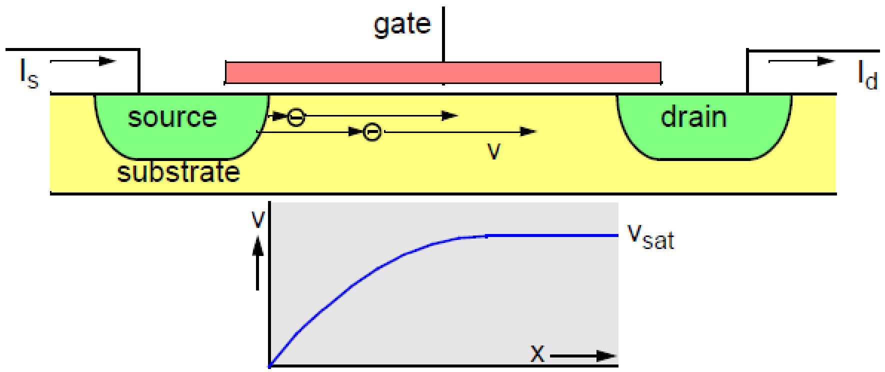


2^{nd} order effects

2^{nd} order effects:

- Velocity saturation:

→ Can be modeled like mobility reduction



$$\mu = \frac{\mu_o}{(1 + (\theta + (\mu_o / v_{max} L))(V_{gs} - V_t))}$$

vertical field | lateral field

mobility reduction | velocity saturation

- maximum possible speed for charge-carriers
- occurs for shorter channel-length and large V_{ds}

- Drain induced barrier lowering

→ Drain become the second gate and influence the channel.

→ Makes the channel to be partially ON and conduct

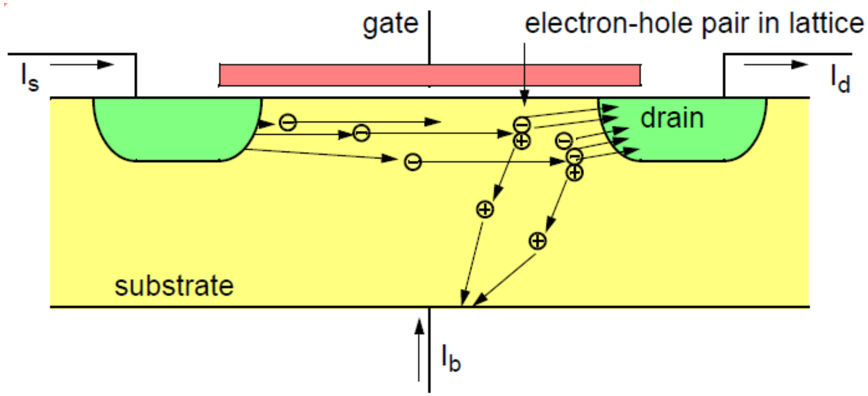
→ lowering VT and increase leakage current.

2nd order effects

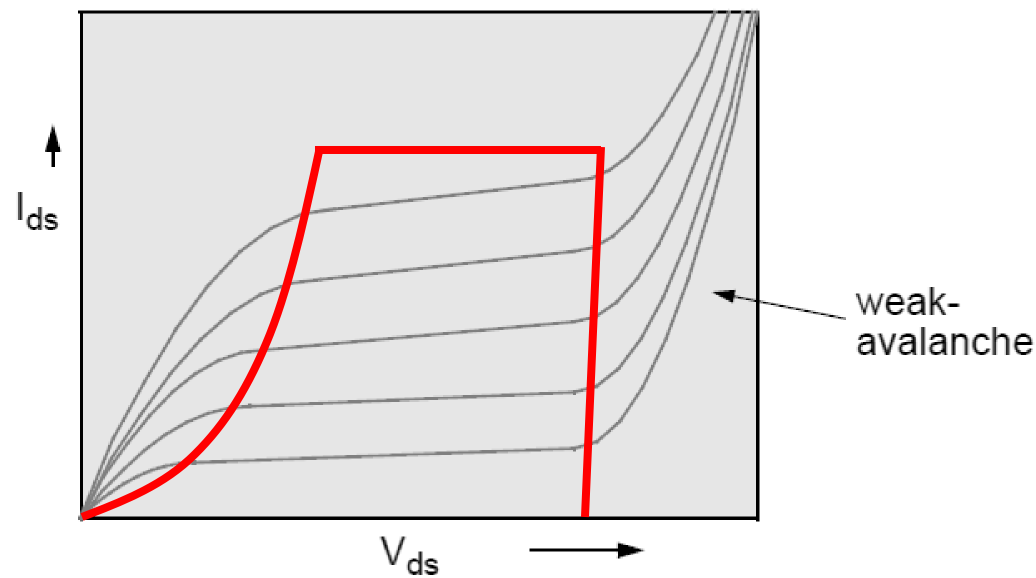
2nd order effects:

- Weak Avalanche:

→ in very short devices, where the horizontal E field is strong.



- generates extra drain-current: $I_d = I_s + I_b$
- occurs for shorter channel-length and large V_{ds}



Subthreshold Swing

How fast a transistor turns off when we lower the gate voltage.

$$SS \equiv \frac{dV_{GS}}{d(\log_{10} I_D)} \quad [\mathrm{mV/dec}]$$

In planar transistors:
it takes ~100 mV to reduce current by 10×
SS → 100mV/dec

$$SS_{\min} = 60\ \mathrm{mV/dec}$$

FinFet:
SS → 70-75mV/dec

GAA:
SS → 65-70mV/dec

Cadence

Goals:

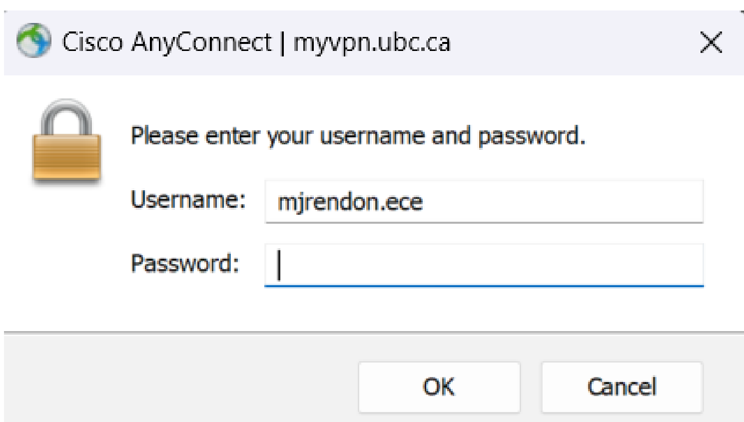
- Access to the UBC ECE SSH server through VPN and X2GO.
- Linux Mini Tutorial.
- Launching Cadence.

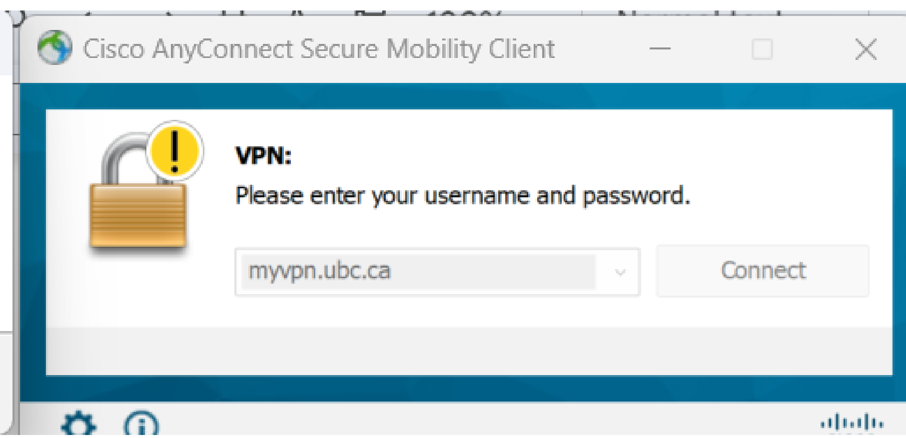
Access to the UBC SSH Server

- **Key resources:**
  - ***AnyConnectVPN:***
    - Official Help ECE UBC Tutorial.
    - Or X2GO proxy option.
  - ***X2GO, Mobaxterm, VNC, XQuartz***
    - Official Help ECE UBC Tutorial.
    - If the download blocked by the Chrome, just click on the keep the files in the downloads tab.

Access to the UBC SSH Server

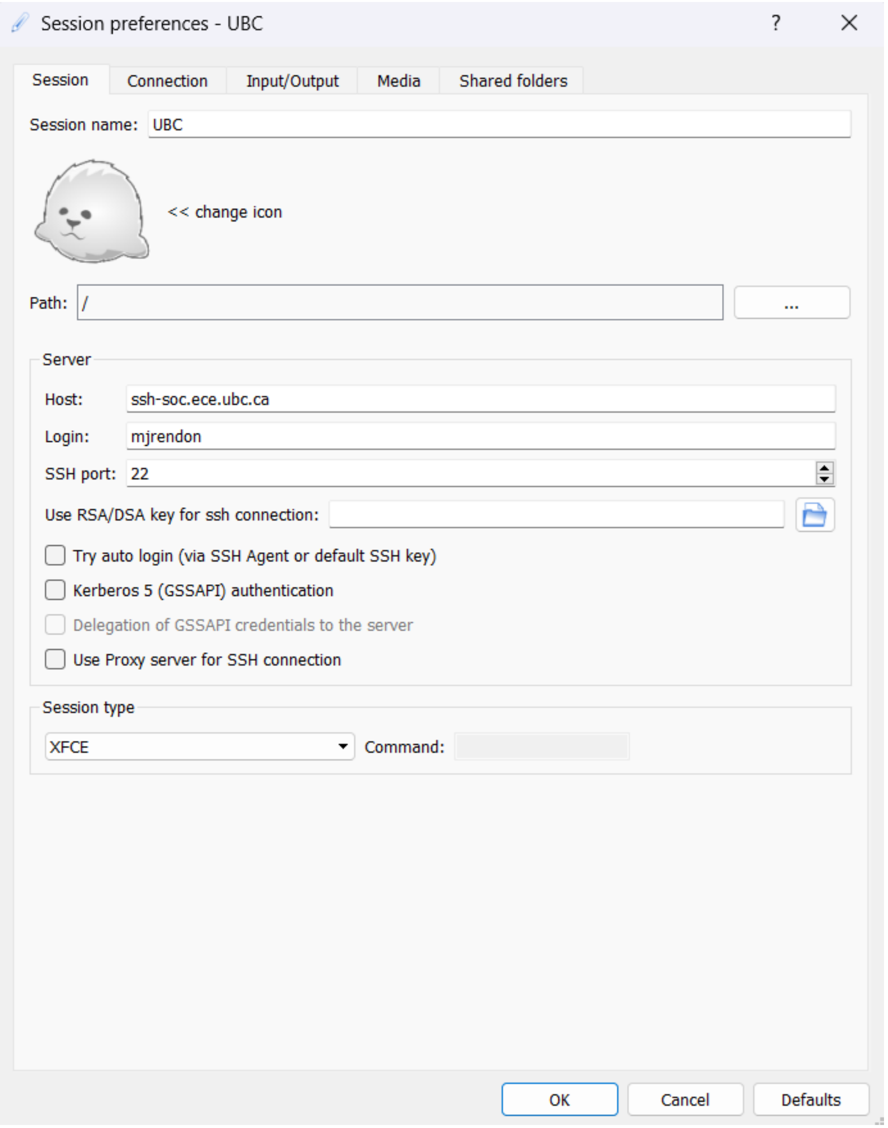
- **1 - AnyConnect VPN**
  - Needed to avoid being blocked by the ECE firewall.
  - For access to the ECE VPN contact it@ece.ubc.ca and specify:
    - Download Cisco ACWL username.
    - Affiliation with ECE.
  - AnyConnect VPN client from https://myvpn.ubc.ca .
  - To connect:
    - The username is <CWL.ece>
    - The password is the same as your CWL.





Access to the UBC SSH Server

- **2 - X2GO**
  - macOS users should download XQuartz (see official UBC tutorial).
  - **Steps:**
    - Download X2GO Client (see official UBC tutorial for links)
    - Install X2GO Client.
    - Configure a new X2GO Session.
    - Once configured, click on the seal and login with you **ECE CREDENTIALS** (Not your CWL credentials).
    - For proxy use: click on use proxy check box and fill



Access to the UBC SSH Server

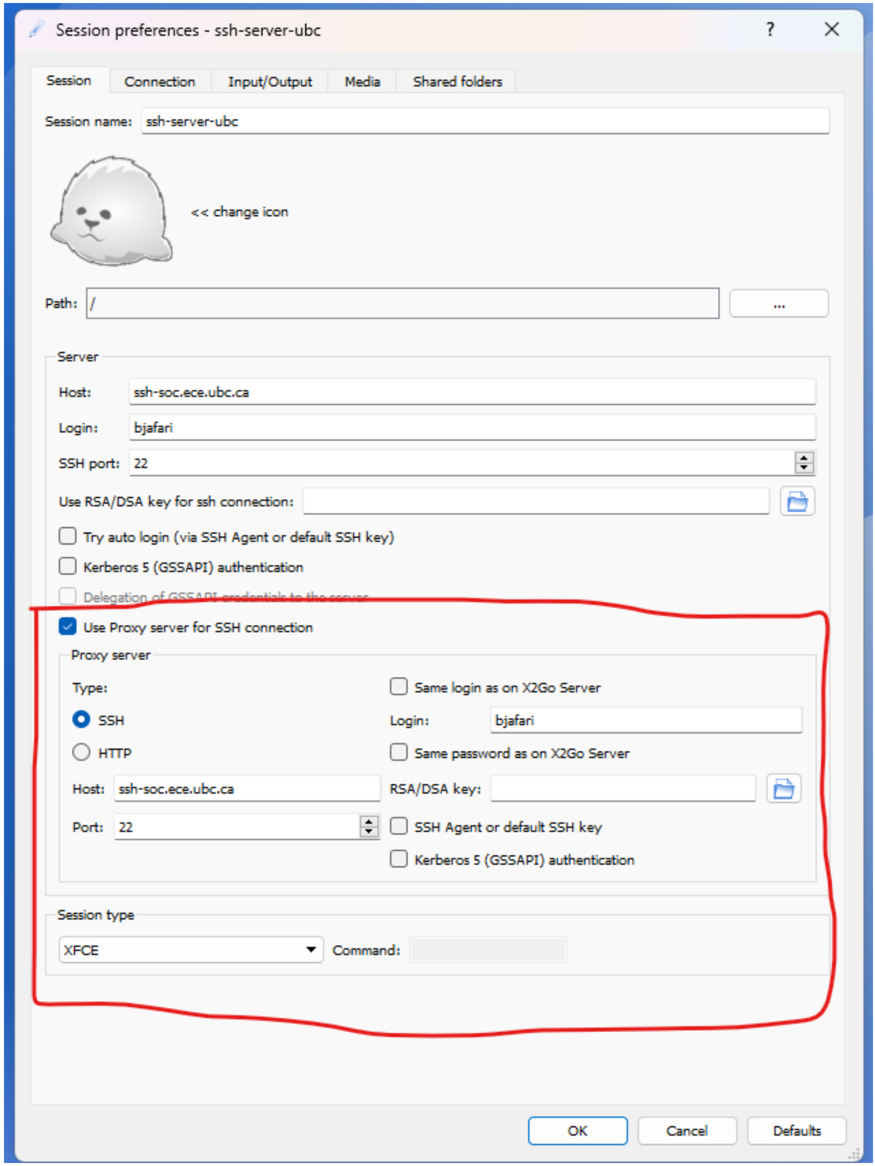
- **2 - X2GO**
  - It is recommended to change the shell of your ECE account from bash to tcsh through this link.

Unix	
Username	mjrendon
User ID	2[redacted]
Group ID	6[redacted]
Home directory	/ubc[redacted]mjrendon
Login shell	/bin/tcsh · Change Shell

- **Additional Information:**
  - If you need to exchange files between your Windows/macOS and the ECE Server, follow this tutorial.

Access to the UBC SSH Server

- **2 - X2GO**
  - Instead of using AnyConnect for remote connection, click on use proxy check box and fill it as follows.



Linux Mini Tutorial - Paths

- In Linux, the most important thing is to navigate through directories.

- **Directories** end with a "/" while **files** do not.
- Each directory (similar to a folder) and file is described by a path.
  - ***Absolute paths*** start with "/" from the root directory
  - ***Relative paths*** start with "./" from the current directory.

- The two most important directories are the following:
  - "." ***current*** directory
  - ".." ***upper*** directory

- Some commands have flags "-" next to them.
- Use the TAB button to autocomplete commands, filenames, and paths.

Linux Mini Tutorial - Navigation

- `pwd`
  - Shows the current working directory

- `ls`
  - Displays the contents of the current directory
  - It hides contents beginning with "."

- `ls -la`
  - Displays all the contents on a list format

- `cd <directory_path>`
  - Changes the directory to <directory_path>
  - Similar to going to another folder
  - For example, "`cd ..`" returns to the upper directory

Linux Mini Tutorial - Directories

- `mkdir <directory_name>`
  - Creates a new directory with the name of `<directory_name>`
  - You can create multiple directories at the same time, just keep adding the paths of the new directories
- `cp -r <source1> <source2> <source3> ... <destination>`
  - Copies the directories `<source1> <source2> <source3>` to `<destination>`
  - The "`-r`" flag is needed to recursively copy all of the contents inside the source directories
  - You can copy multiple directories but the last path will always be the destination
- `rm -r <source1> <source2> <source3> ...`
  - Removes the directories `<source1> <source2> <source3>`
  - The "`-r`" flag is needed to recursively remove all the contest inside the directories
  - You can delete multiple directories at the same time
- `mv <source> <destination>`
  - Moves the directory `<source>` to `<destination>`
  - Can also be used to rename the `<source>` directory

Linux Mini Tutorial - Files

- `touch <filename.extension>`
  - Creates a file of any extension
- `cp <source1> <source2> <source3> ... <destination>`
  - Copies multiple files to a single destination
- `rm <source1> <source2> <source3> ...`
  - Removes multiple files
- `mv <source> <destination>`
  - Moves files from the <source> to the <destination>
  - Can be used to renamed the <source> file
- `cat <filename>`
  - Displays the contents of a file
- `source <filename>`
  - Runs the contents of a file
- `vim <filename>`
  - Text editor to edit files

Linux Mini Tutorial - Vim

- Press "`i`" to enter "insert mode" where you can write and delete text in your file.
  - - A "-- INSERT --" message will appear.
  - - Use ESC to exit insert mode.
- `/<term>`
  - - Highlights all the instances of <term> inside the file.
  - - Use "`N`" to go to the next instance and "`SHIFT + N`" to return to the previous instance.
- `u`
  - - Undoes work you have done on the file.
- `:set number`
  - - Displays the line numbers at the left of the file.
- `:w`
  - - Saves the file.
- `:q`
  - - Quits and exists VIM.
  - - Only works if the file has been saved.
  - - Use ":q!" to quit and avoid saving changes.
- On csh files:
  - echo “text” displays text when sourcing

How to run Cadence and 45nmGPDK

- In your home directory, create a new folder (e.g., ELEC401), then run the terminal by right clicking on the screen.
- Run this script: source /CMC/scripts/kit.gpdk45_OA.csh
- A massage like this will show up:
  virtuoso -log /ubc/ece/home/sm/grads/bjafari/CDSlogs/53282 &
- Copy/paste and run it to launch the cadence.

- These are basic cadence tutorials. Do an inverter simulation by yourself. If you have any problem, we will discuss in the next TA class session.

https://www.youtube.com/watch?v=u0WgSMa1hrc&list=PLK2eyR1C9gjr7j-YoL_-JwJmjU6lNZGTO&index=1

https://www.youtube.com/watch?v=IGcHR1I17ok&list=PLK2eyR1C9gjr7j-YoL_-JwJmjU6lNZGTO&index=2