Analog Electronics

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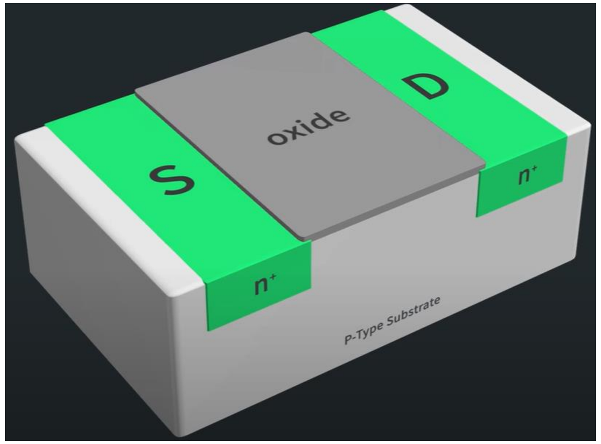
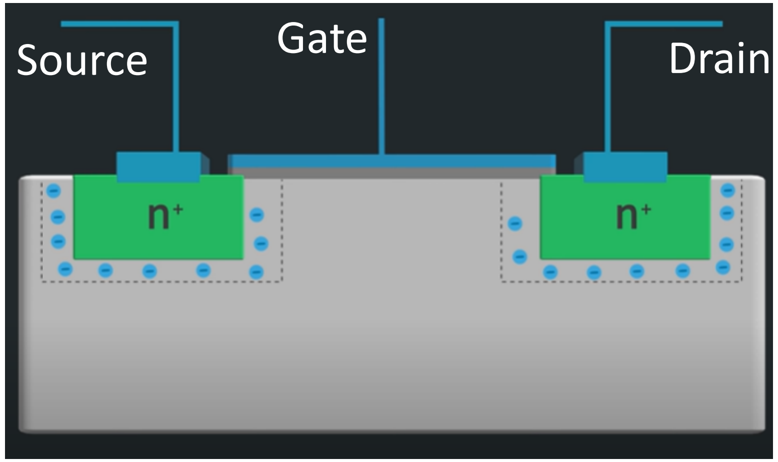
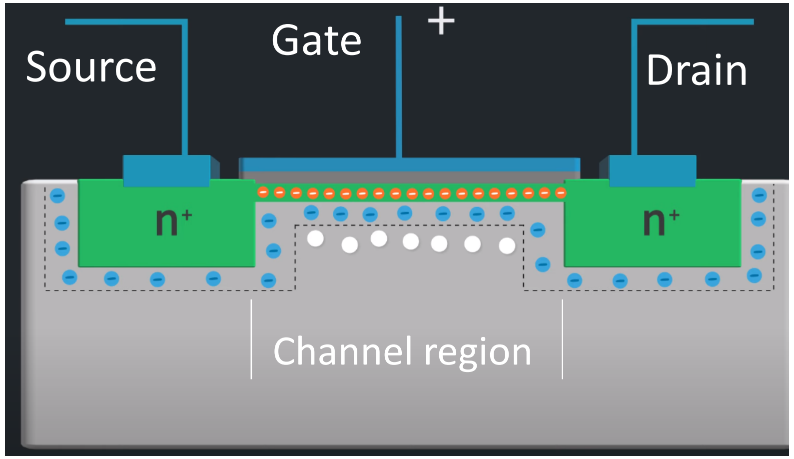
Agenda

- Introduction to enhancement MOSFET
  - Structure and operation regions
  - Large & small signal model
- MOSFET VS. BJT
- Frequency response of circuit

Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)



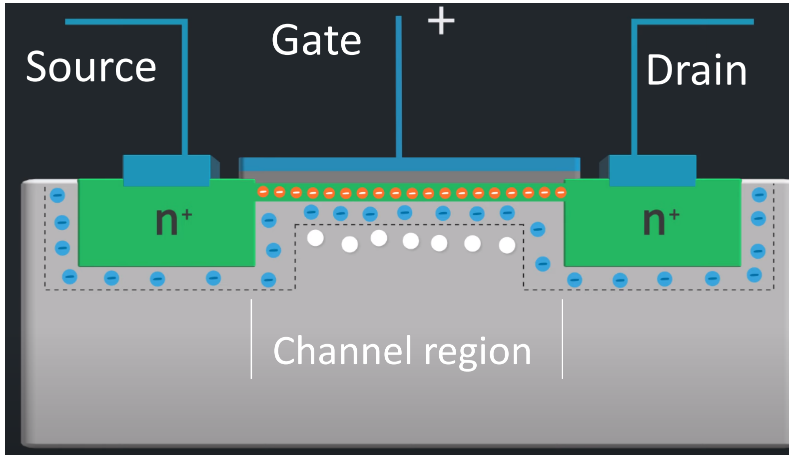


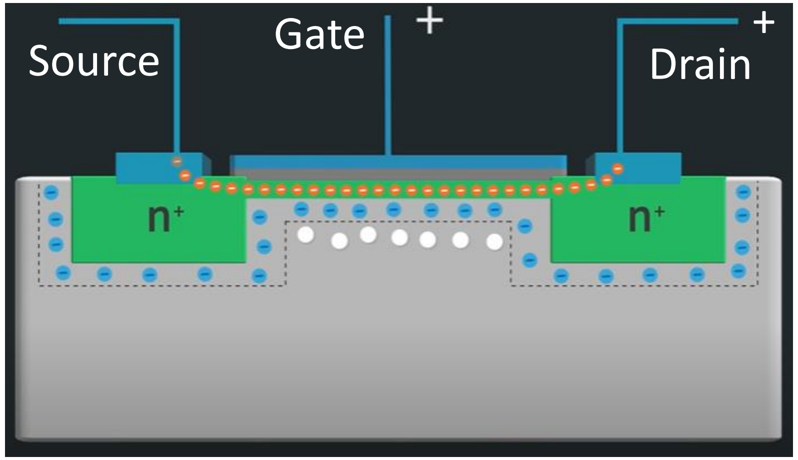


$V_G < V_{TH}$ ➔ 'cut-off' region

$V_G > V_{TH}$ ➔ A channel

Metal-Oxide-Semiconductor Field-Effect Transistor (MOSFET)





$V_G > V_{TH}$ & $V_{DS} = 0$

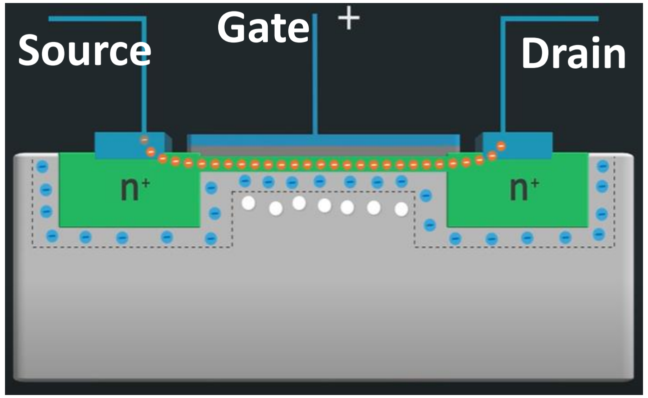
Turn on but no current

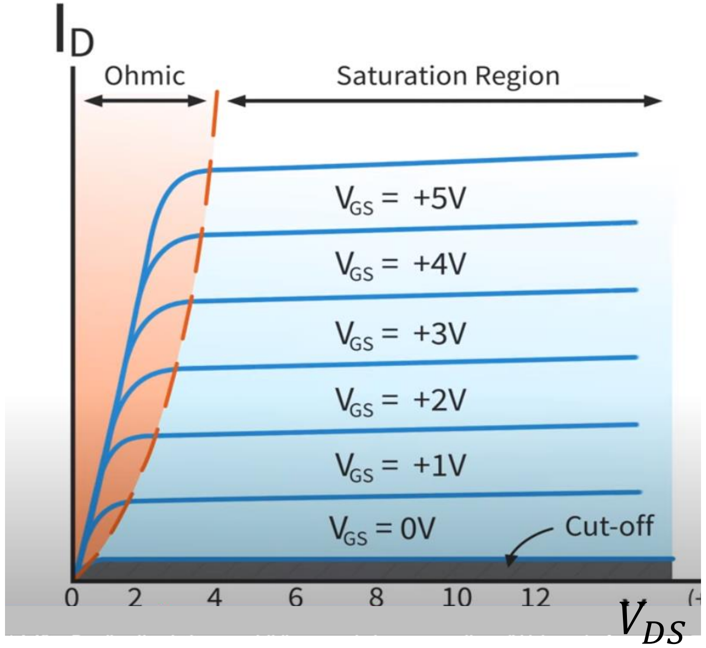
$V_G > V_{TH}$ & $V_{DS} > 0$

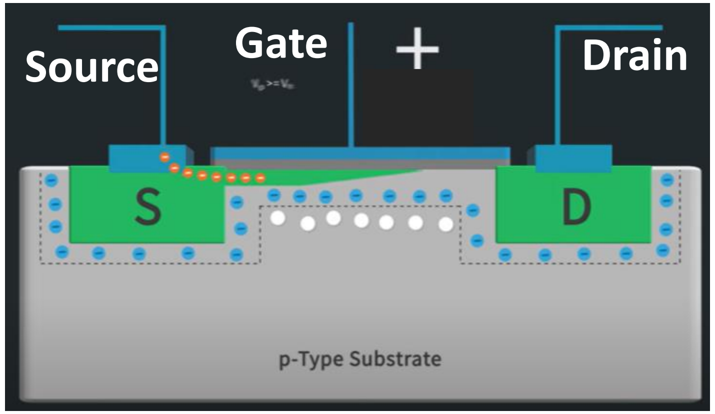
The current flows from D to S.

Enhancement MOSFET: increasing gate voltage ‘enhances’ the channel conductivity.
As V_G increases, electron density in channel increases ➔ resistance between S and D decreases.
A voltage controlled current source.

Operation regions of MOSFET





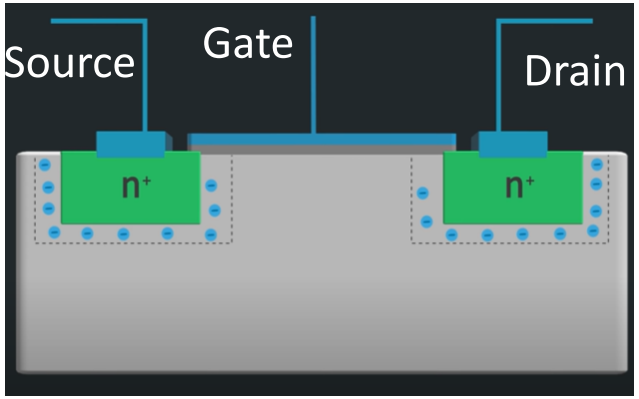


Triode or ohmic region: $V_{GD} > V_{TH}$

$$I_D = k_n[(V_{GS} - V_{TH})V_{DS} - \frac{1}{2}V_{DS}^2]$$

Saturation region: $V_{GD} < V_{TH}$

$$I_D = \frac{1}{2}k_n\,(V_{GS} - V_{TH})^2(1 + \lambda V_{DS})$$



Cut-off region: $V_{GS} < V_{TH}$

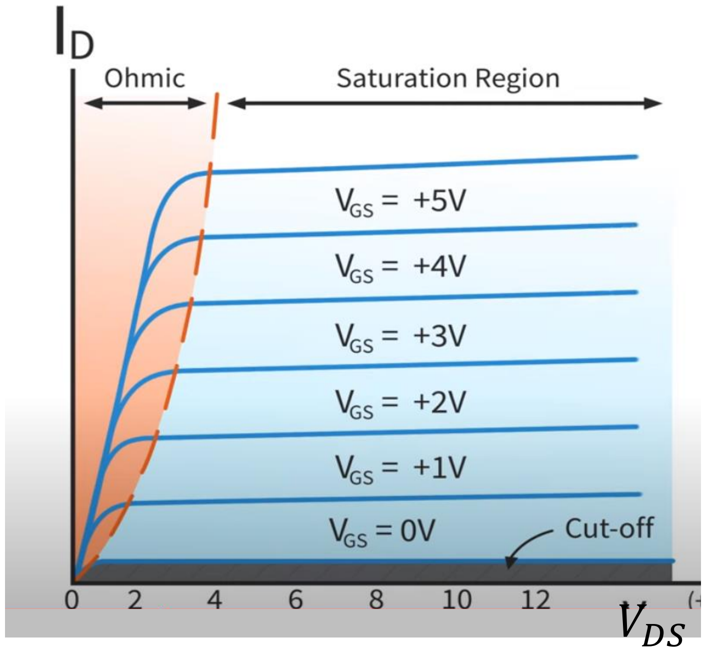
I_D = 0

- $\lambda = \frac{L - L'}{V_{DS}L}$: channel length modulation coefficient
- L': actual channel length

Triode and cut-off region: switching devices

Saturation region: amplifier

Operation regions of MOSFET



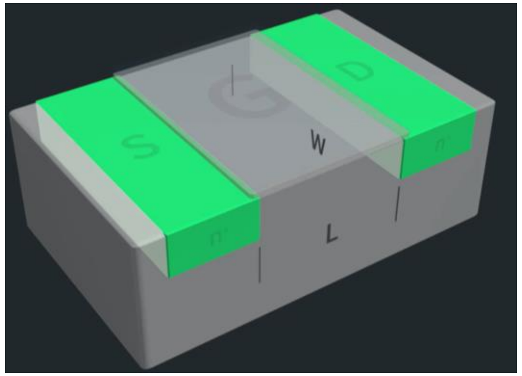
MOSFET transconductance parameter:

$$k_n = \mu_n C_{ox} W/L$$

- μ_n: mobility of the electrons at the surface of the channel
- C_{ox}: oxide capacitance
- W & L: width & length of the channel

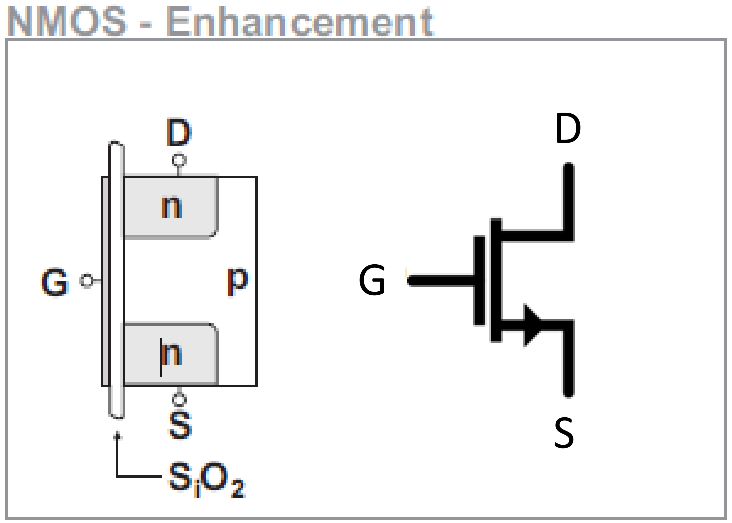
Overdrive voltage: $V_{ov} = V_{GS} - V_{TH}$

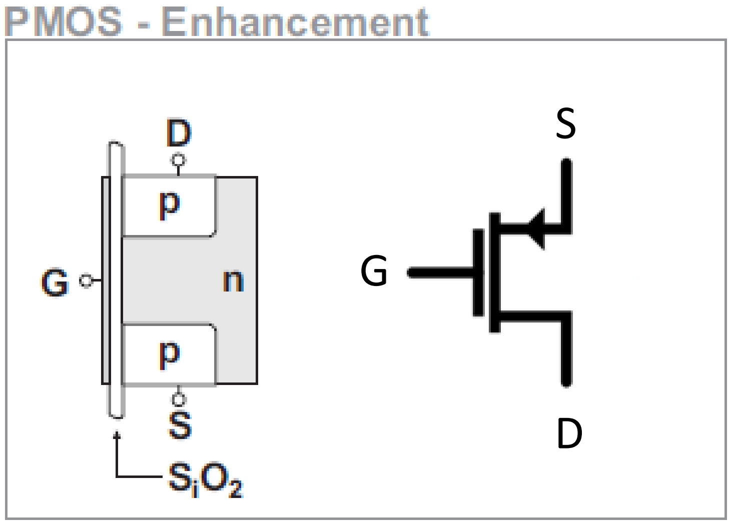
Threshold voltage: V_{TH}----0.3 V ~ 1V



$$I_D = \begin{cases} 0, & \text{cut-off: } V_{GS} < V_{TH} \\ k_n\left[(V_{GS}-V_{TH})V_{DS} - \frac{1}{2}V_{DS}^2\right], & \text{triode: } V_{GD} > V_{TH} \\ \frac{1}{2}k_n(V_{GS}-V_{TH})^2(1+\lambda V_{DS}), & \text{saturation: } V_{GD} < V_{TH} \end{cases}$$

MOSFET-- symbol





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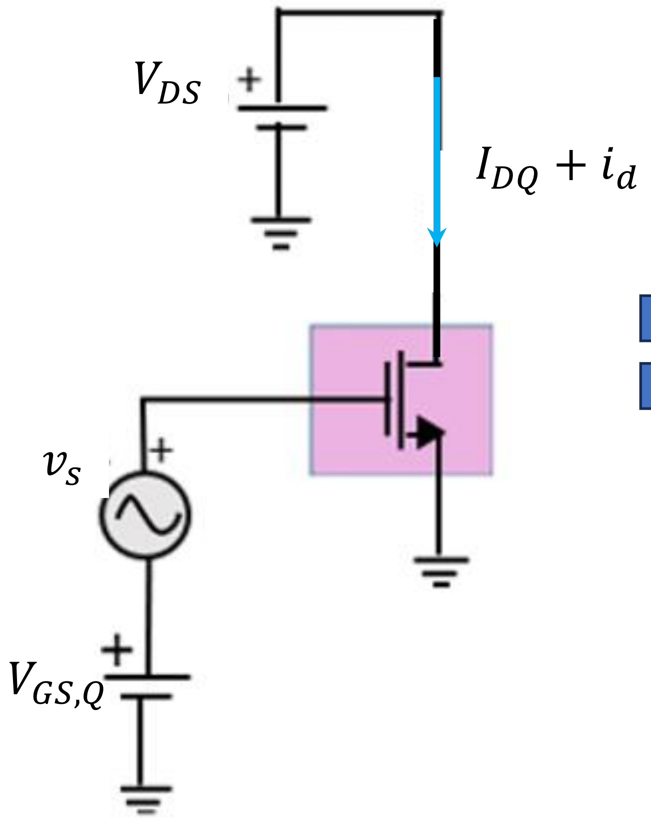
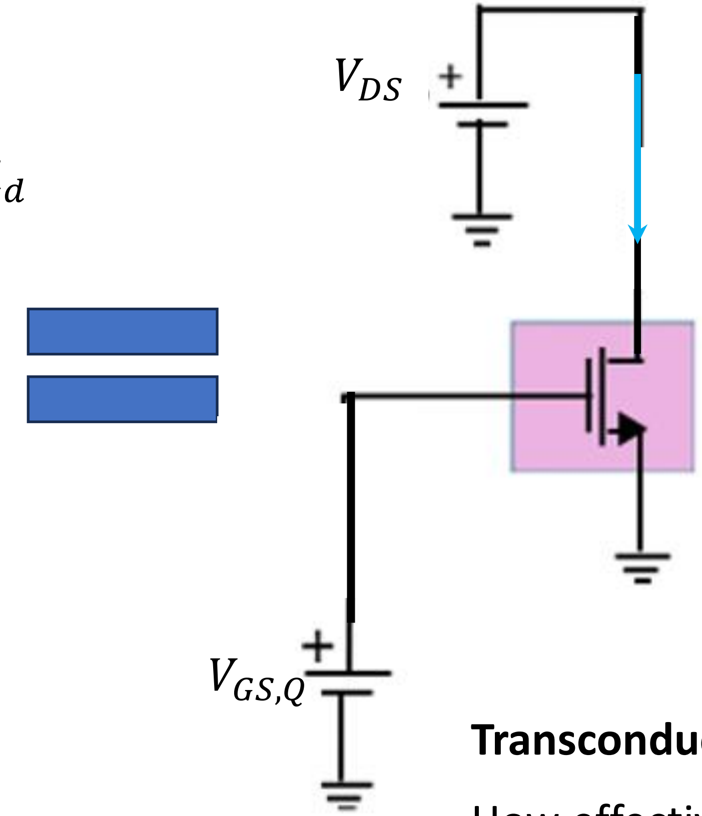
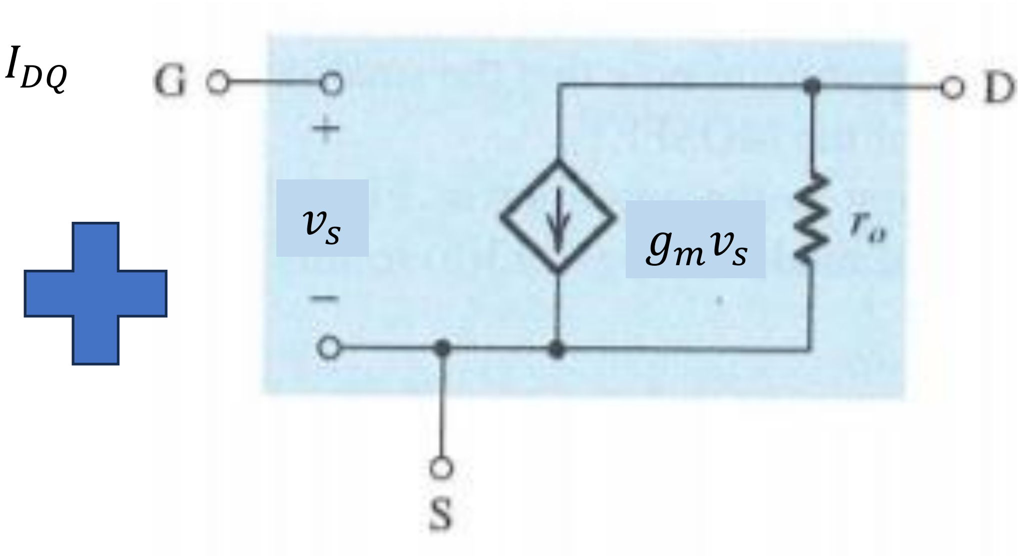
MOSFET—small-signal model







$V_{GS,Q} + v_s - V_{DS} \leq V_{TH}$
In saturation region

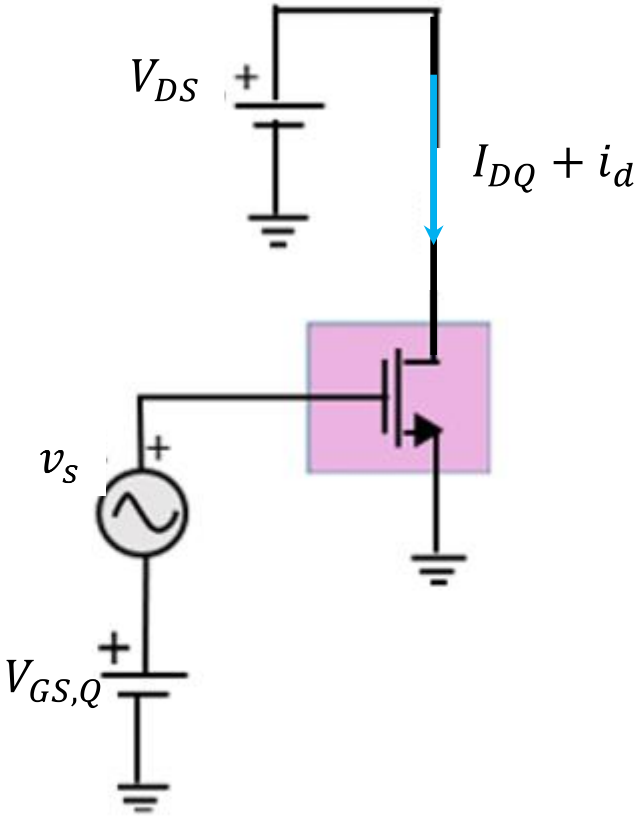
Transconductance $g_m = \frac{\Delta I_D}{\Delta V_{GS}} = \frac{2I_{DQ}}{V_{GS,Q} - V_{TH}} = k_n(V_{GS,Q} - V_{TH})$

How effectively the MOSFET converts a change in V_{GS} into a change in I_D.

Output resistance: $r_o = \frac{\Delta V_{DS}}{\Delta I_D} = \frac{v_s}{i_d} = \frac{1}{I_{DQ}\lambda}$

Quiz

Which operating point is preferred, $Q1$ or $Q2$?



$V_{GS,Q} + v_s - V_{DS} \leq V_{TH}$
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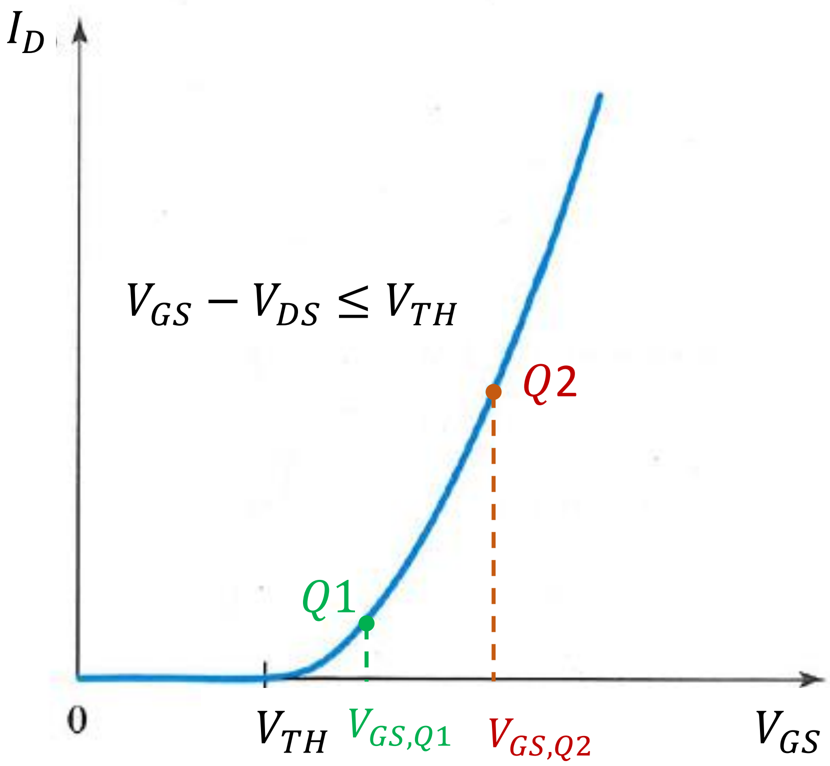

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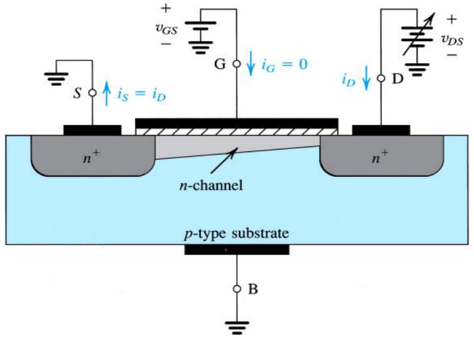
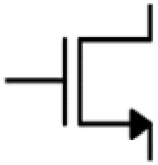
MOSFT VS. BJT

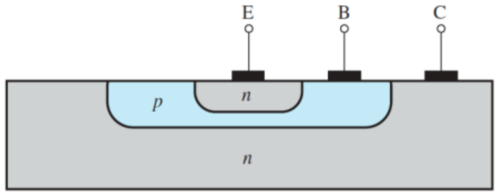
Structure

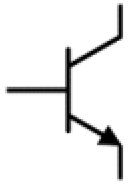
MOSFT: N-type or P-type





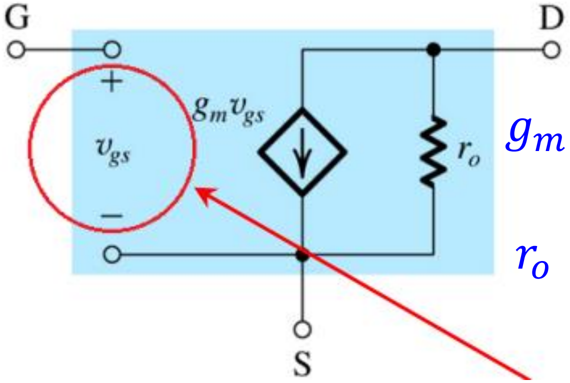
BJT: NPN or PNP





	MOSFT	BJT
Symmetric fabrication	Yes	No
Dominant I-V characteristics	$I_D = \frac{1}{2} k_n (V_{GS} - V_{TH})^2 (1 + \lambda V_{DS})$ – Saturation	$I_C = I_s(e^{\frac{V_{BE}}{V_T}} - 1)$ — forward active
Current control	No current flowing through G and S. The voltage of GS that controls the current through D and S.	A small current flowing through B and E controls a much larger current through C and E.

Small-signal model



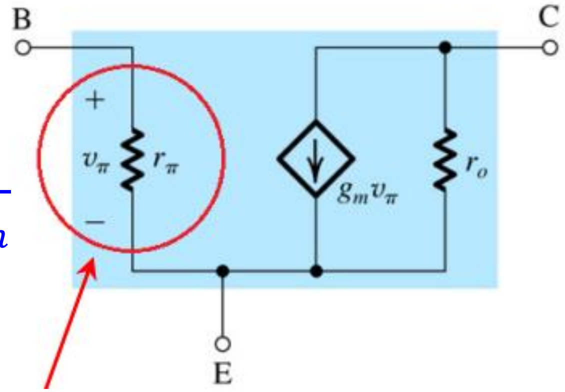
$$g_m = \frac{2I_{DQ}}{V_{GS,Q} - V_{TH}}$$

$$r_o = \frac{1}{I_{DQ}\lambda}$$

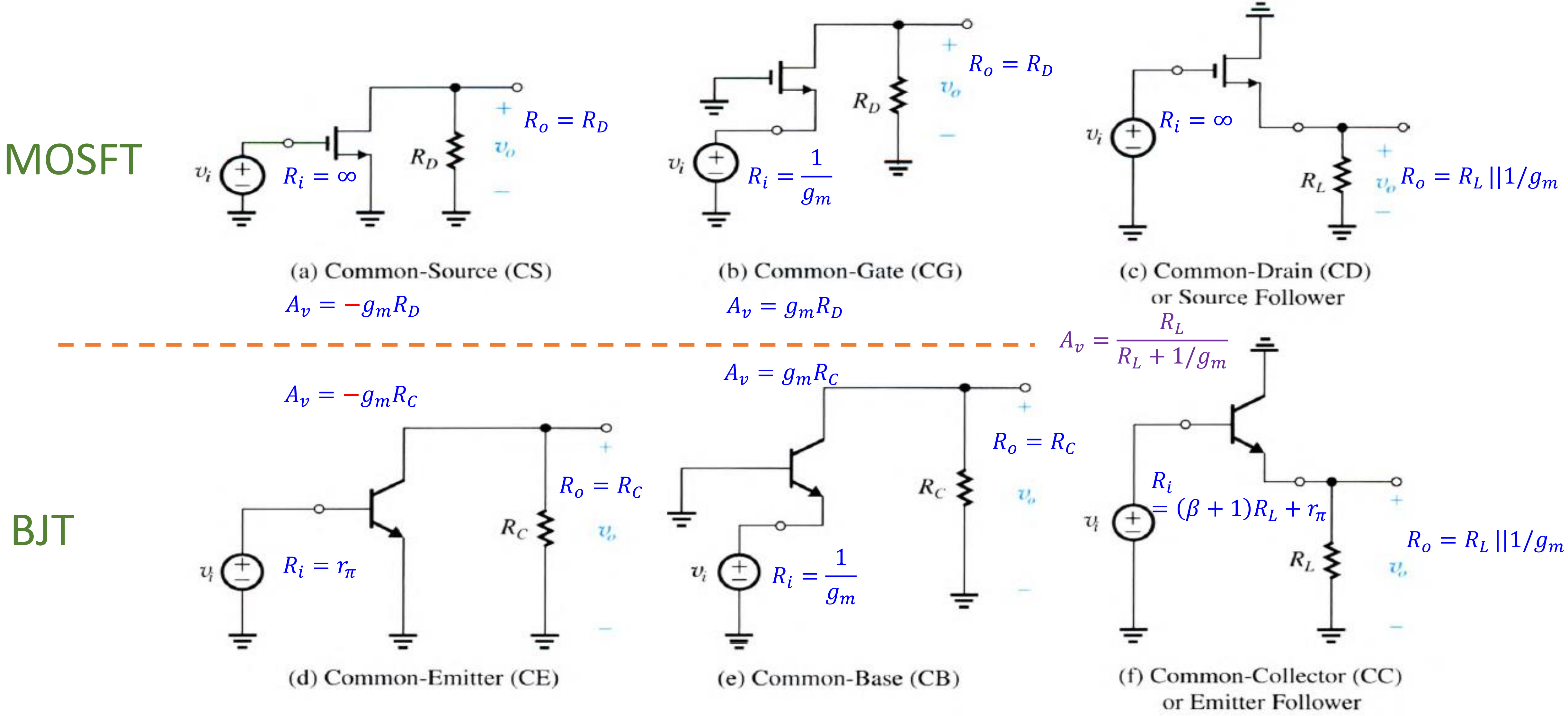
$$g_m = \frac{I_{CQ}}{V_T}$$

$$r_\pi = \frac{V_T}{I_B} = \frac{\beta}{g_m}$$

$$r_o = \frac{V_A}{I_{CQ}}$$



Three basic configurations: MOSFT VS. BJT



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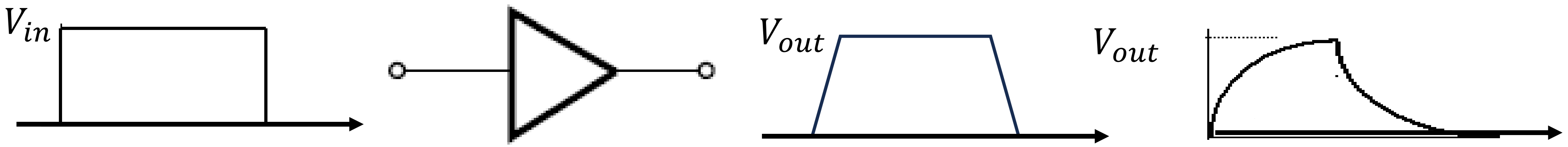
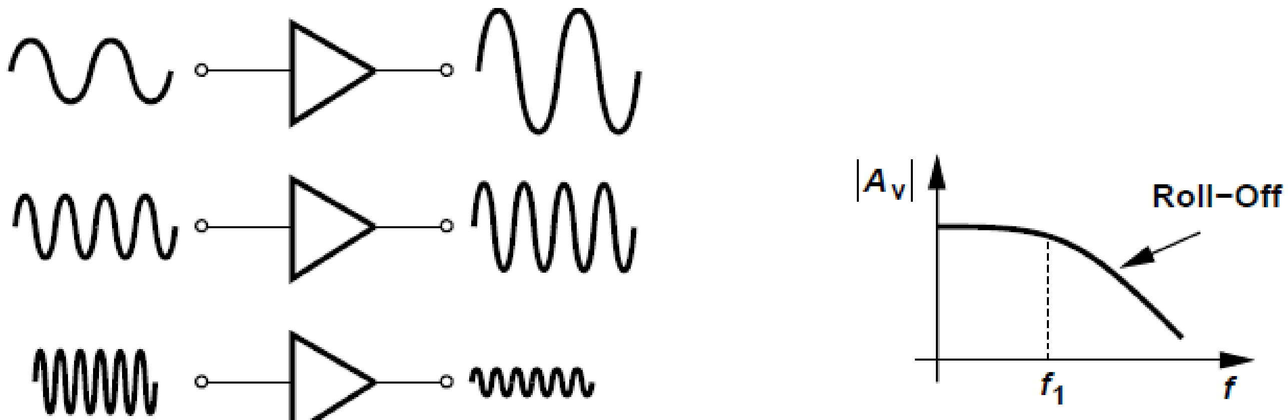
Frequency response —'speed limitation'

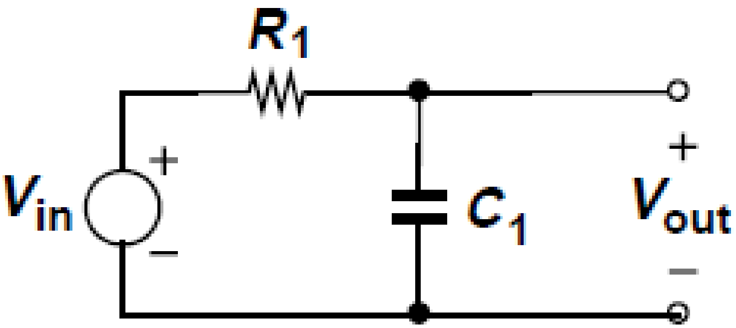


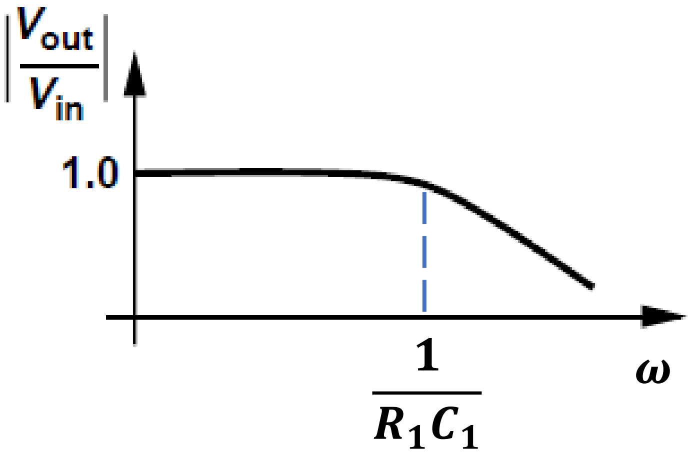


(a) (b)

Gain of transistors is not constant over frequencies.

Frequency response





Time-domain analysis

$$V_{out}(t) = V_{in}(t) - I_1(t)R_1$$
$$= V_{in}(t) - R_1C_1\frac{dV_{out}(t)}{dt}$$

Frequency-domain analysis

$$V_{out}(s) = \boxed{\frac{\frac{1}{C_1 s}}{R_1+\frac{1}{C_1 s}}} V_{in}(s)$$

Transfer function of the circuit

$$H(s) = \frac{1}{1+sR_1C_1} \rightarrow \quad H(j\omega) = \frac{1}{1+j\omega R_1C_1}$$

Transfer function and frequency response

- The transfer function of a circuit:

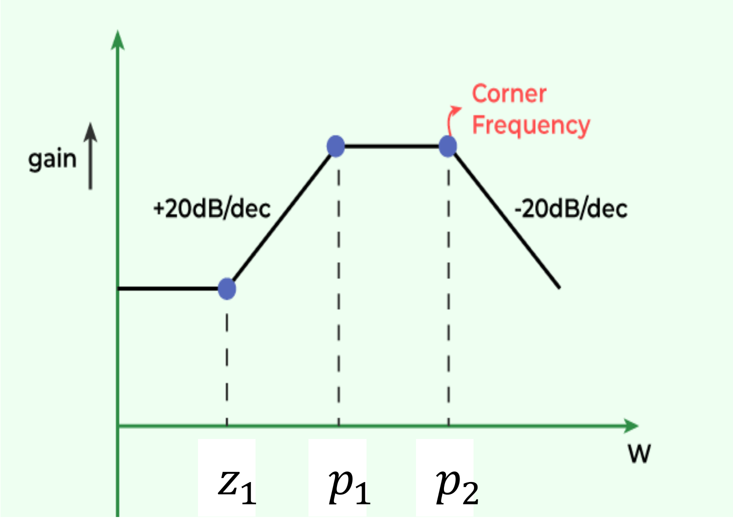
$$H(s)=\frac{Y(s)}{X(s)}=A_0\frac{(s-z_1)(s-z_2)\ldots(s-z_M)}{(s-p_1)(s-p_2)\ldots(s-p_N)}$$

$$A(\omega)=|H(j\omega)|=|A_0\frac{(j\omega-z_1)(j\omega-z_2)\ldots(j\omega-z_M)}{(j\omega-p_1)(j\omega-p_2)\ldots(j\omega-p_N)}|$$

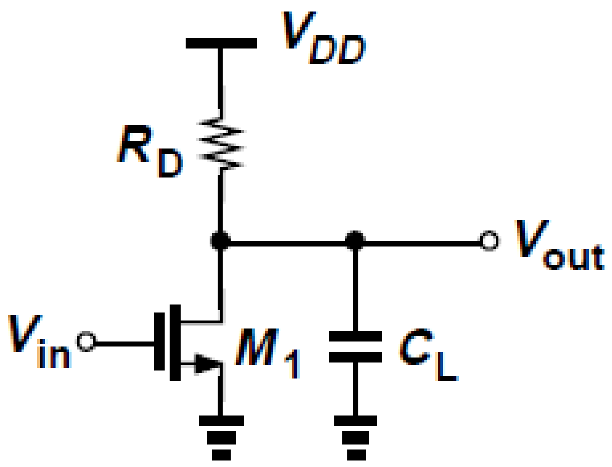
$$\omega=2\pi f$$

z_m and p_n are zeros and poles

Bode's rules to fast construct $A(\omega)$ plot approximately:
As ω passes a **pole** / **zero**, the slope $A(\omega)$ **decreases** / **increases** by 20 dB/dec.

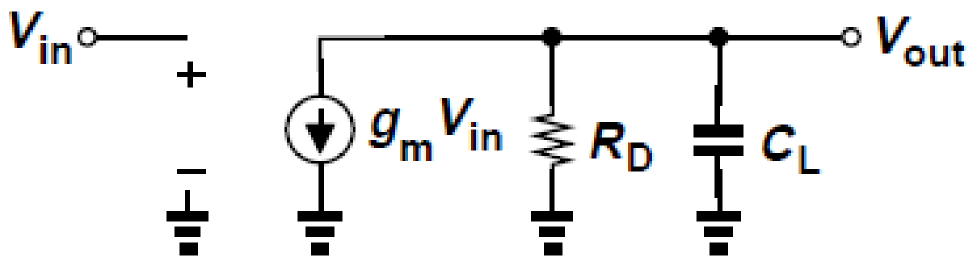


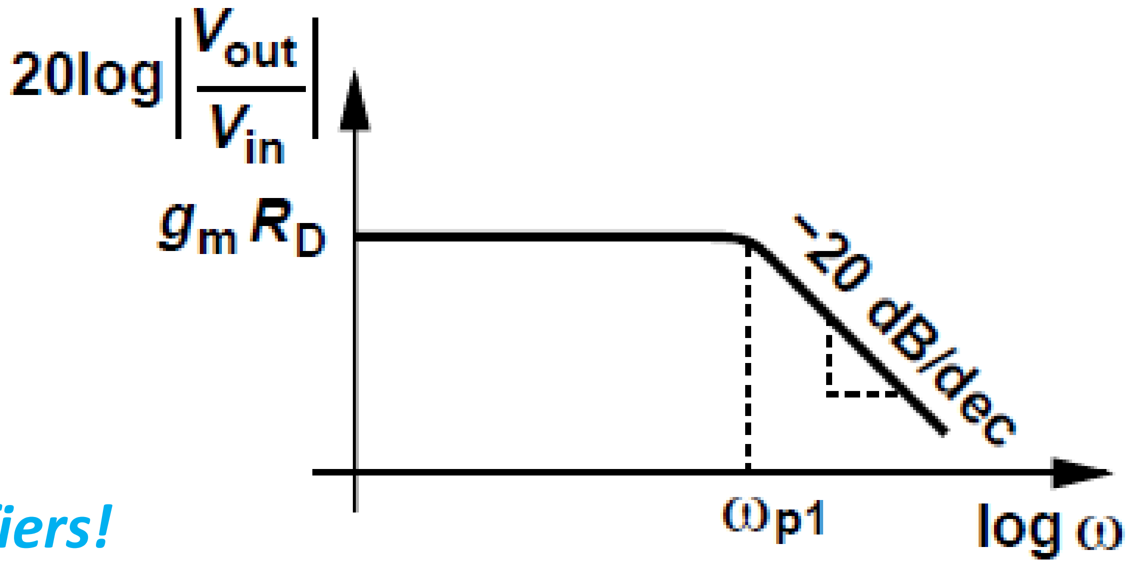
Example



$$A(\omega) = \left| -\frac{g_m R_D}{j\omega R_D C_L + 1} \right| = \frac{g_m R_D}{\sqrt{(\omega R_D C_L)^2 + 1}}$$

$$|\omega_{p_1}| = \frac{1}{R_D C_L}$$

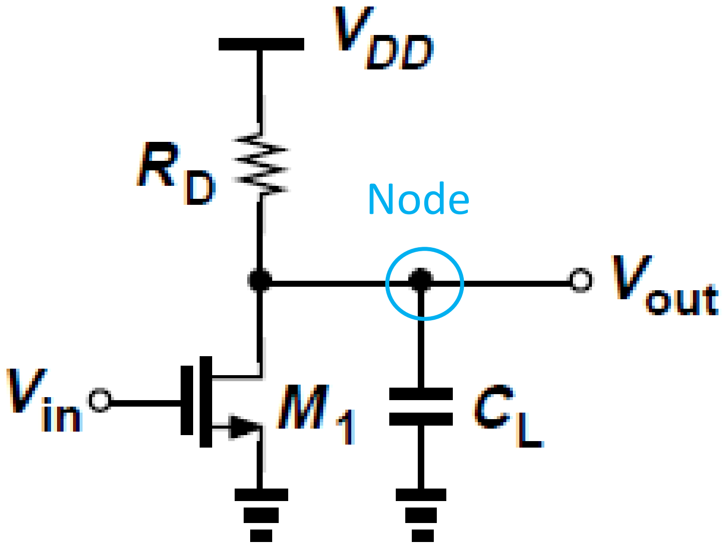




Capacitors generally limit the BW of amplifiers!

Finding poles by inspection

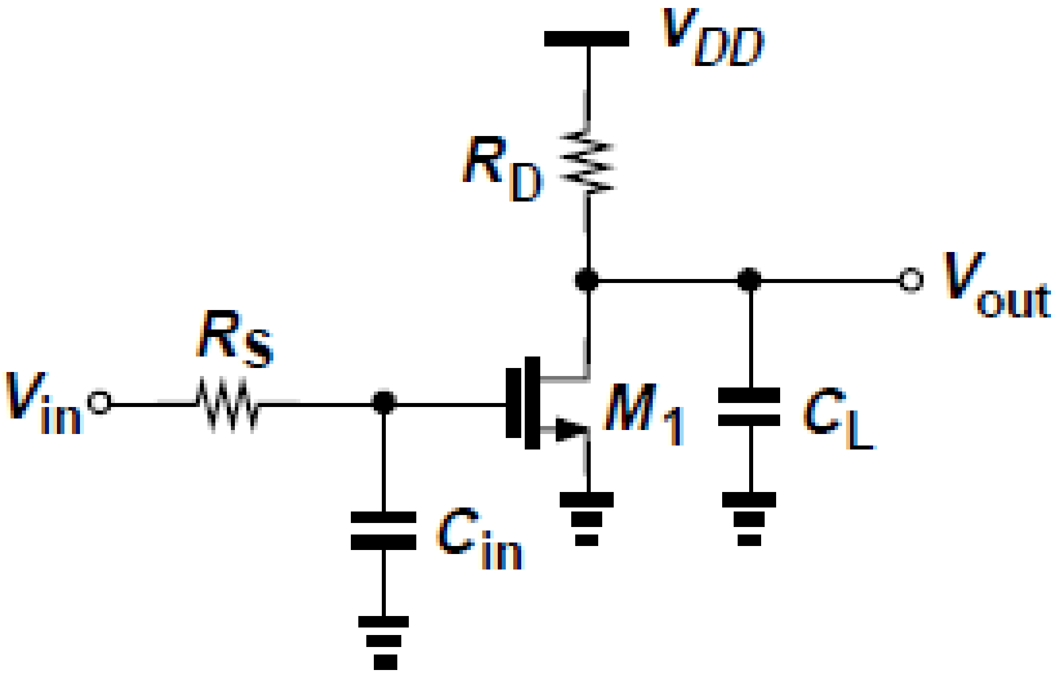
- Set all independent source to 0:
  - voltage source ➔ short circuit; Current source ➔ open circuit.
- Find capacitors connected between the node and AC ground.
- Find resistors connected between that node and AC ground.



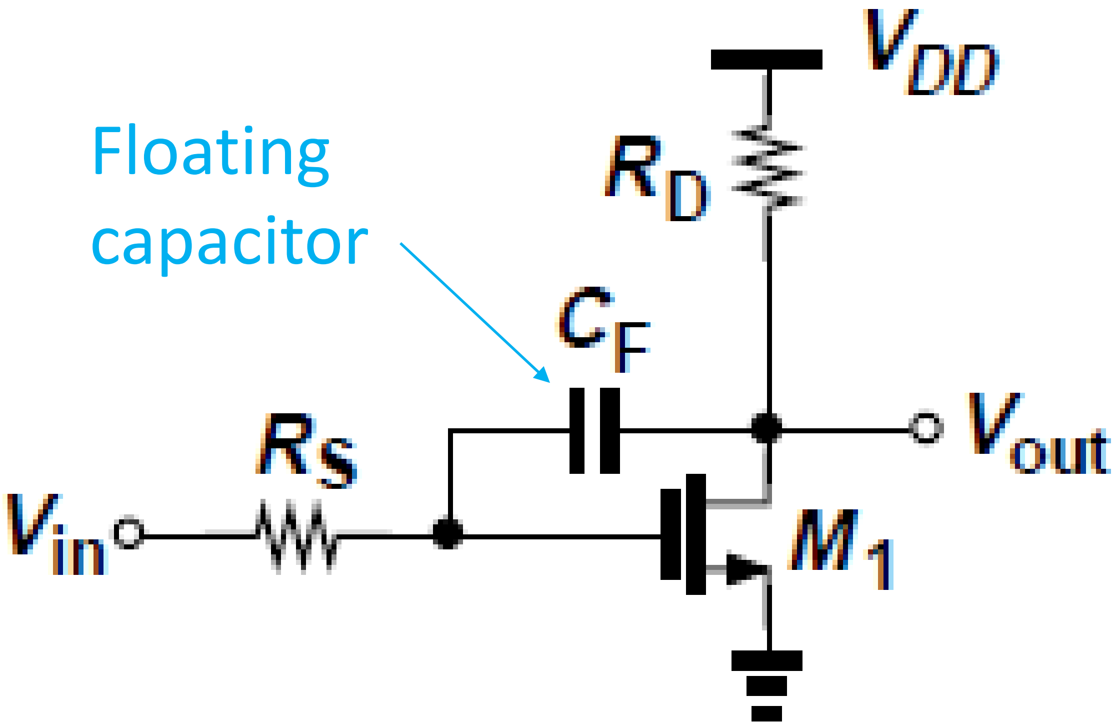
$$\omega_p = \frac{1}{R_D C_L}$$

$$H(\omega) = \frac{V_{out}}{V_{in}}(\omega) = -\frac{g_m R_D}{1 + s/\omega_p}$$

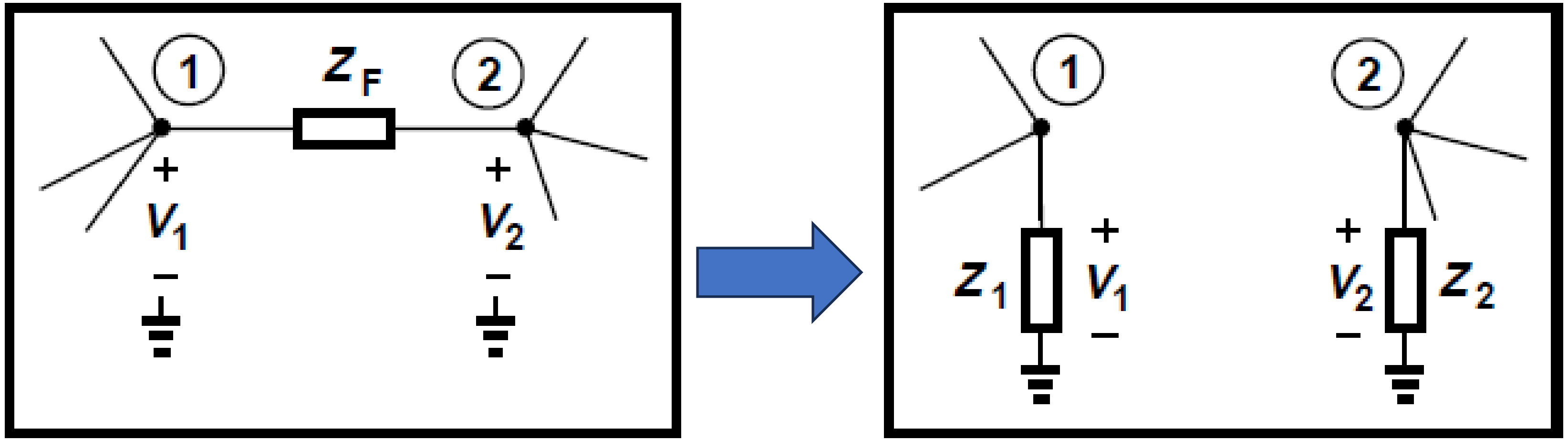
Quiz: find the poles and plot $|H(j\omega)|$



Can we find the poles?



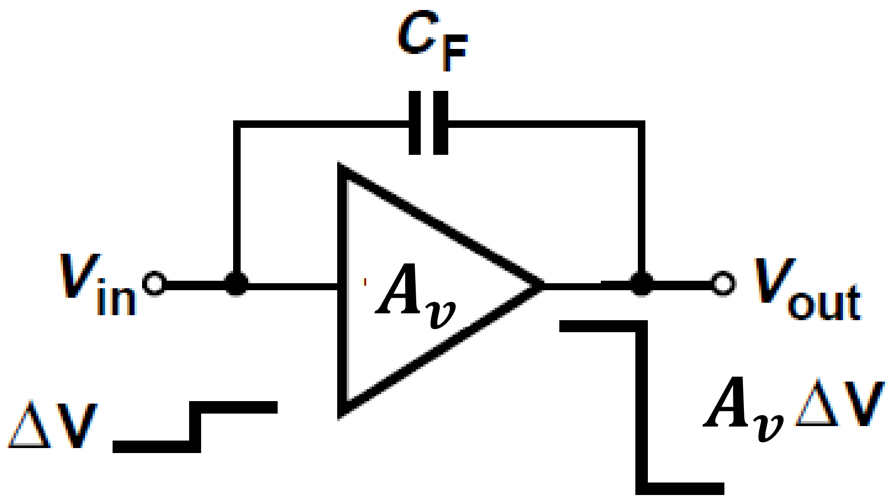
Miller’s theorem

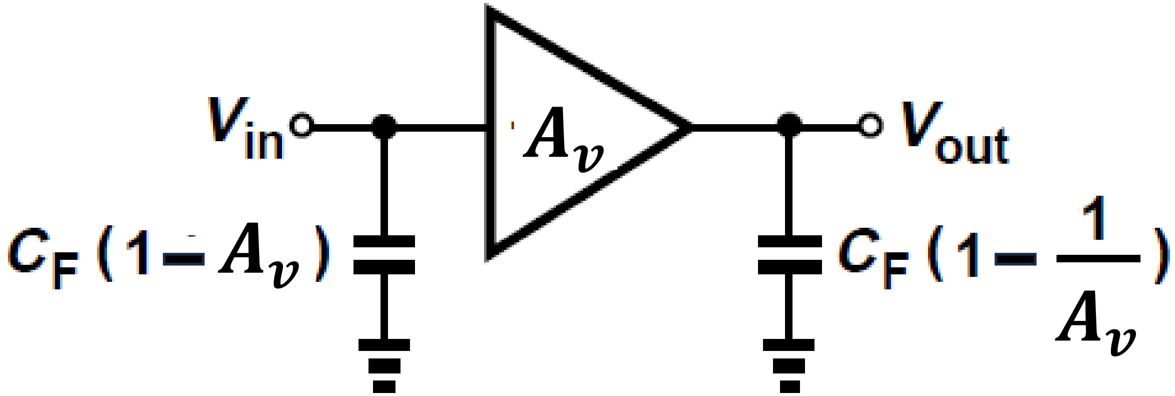


Decompose a floating capacitor to two grounded capacitors.

$$Z_F \Rightarrow Z_1 \;\&\; Z_2$$

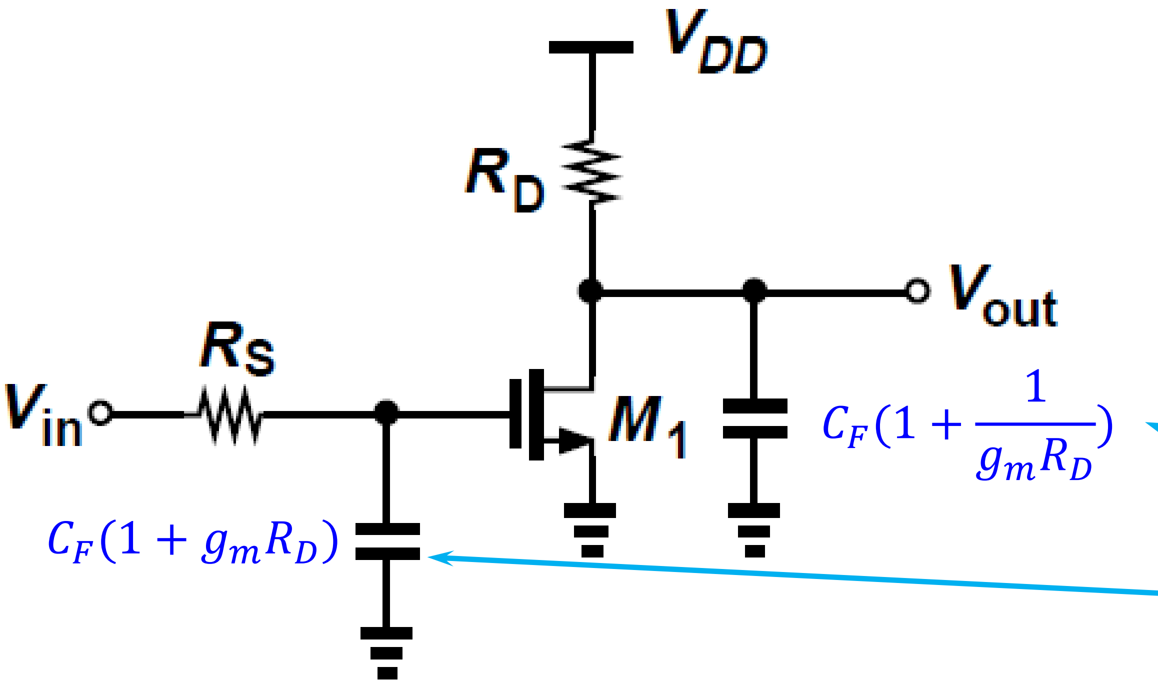
Example

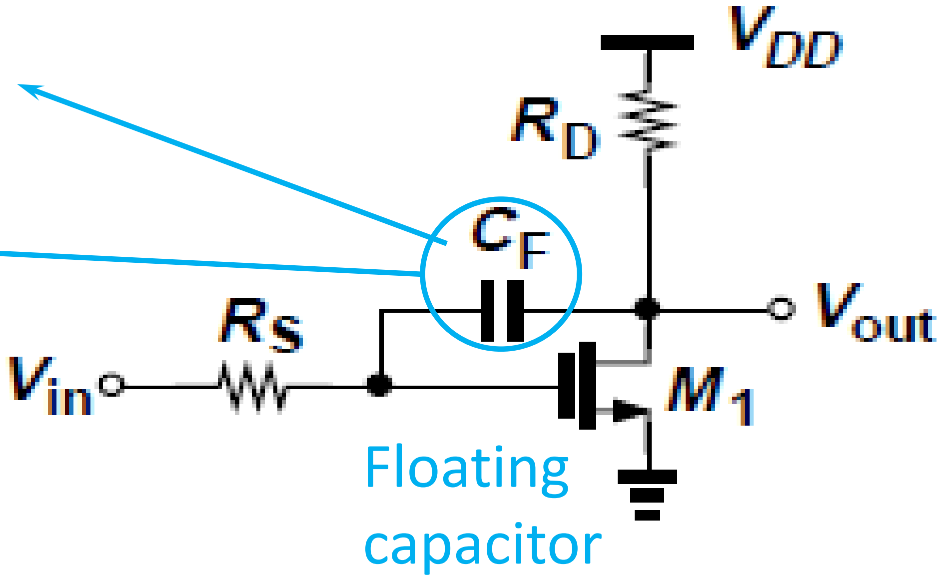




$A_v = \mathrm{V_{out}/V_{in}}$

We can find the poles by Miller's approximation





$$A_v = -g_m R_D$$

The role of capacitors

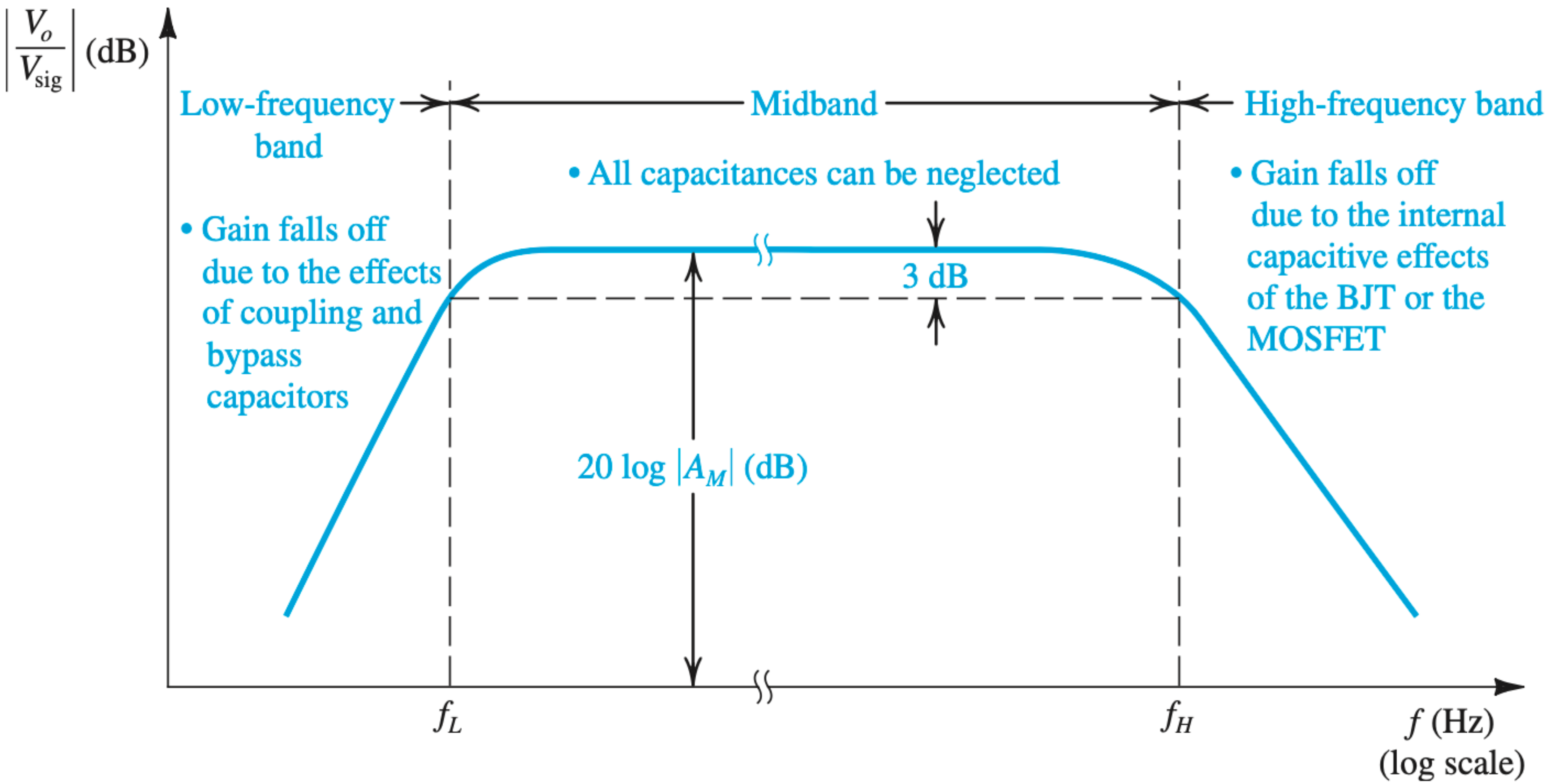
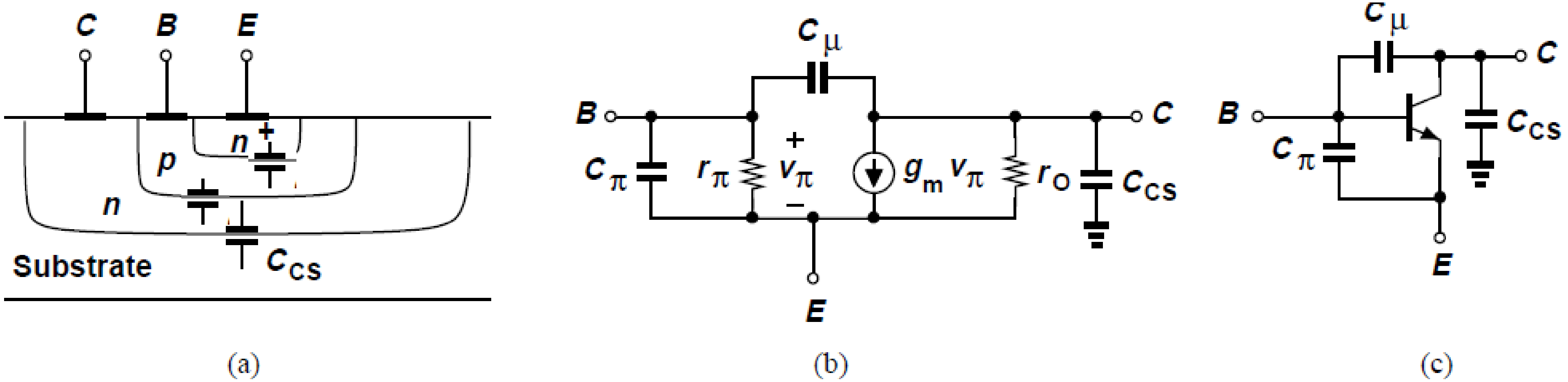


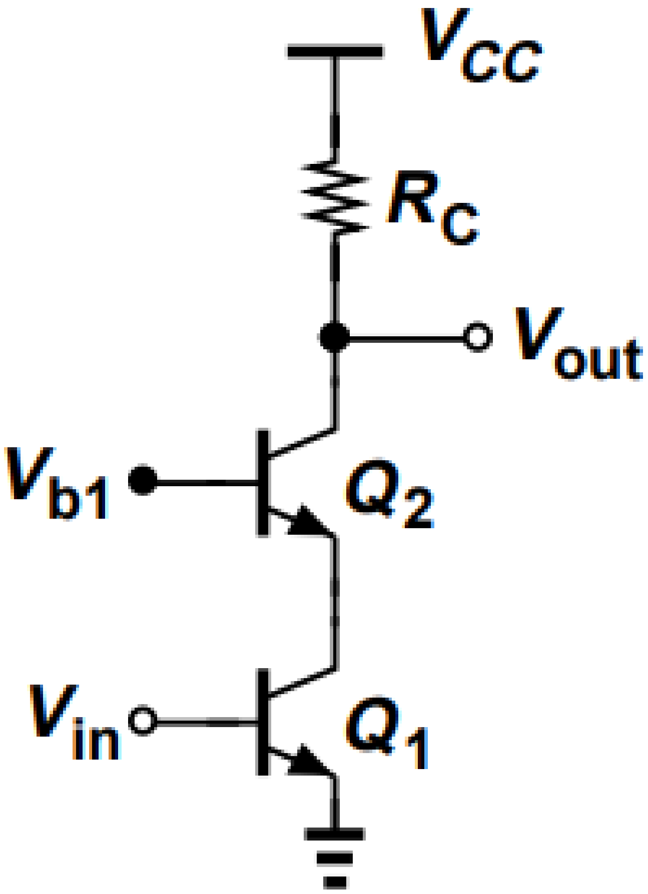
Figure 10.1 Sketch of the magnitude of the gain of a discrete-circuit BJT or MOS amplifier versus frequency. The graph delineates the three frequency bands relevant to frequency-response determination.

High-frequency models of BJT

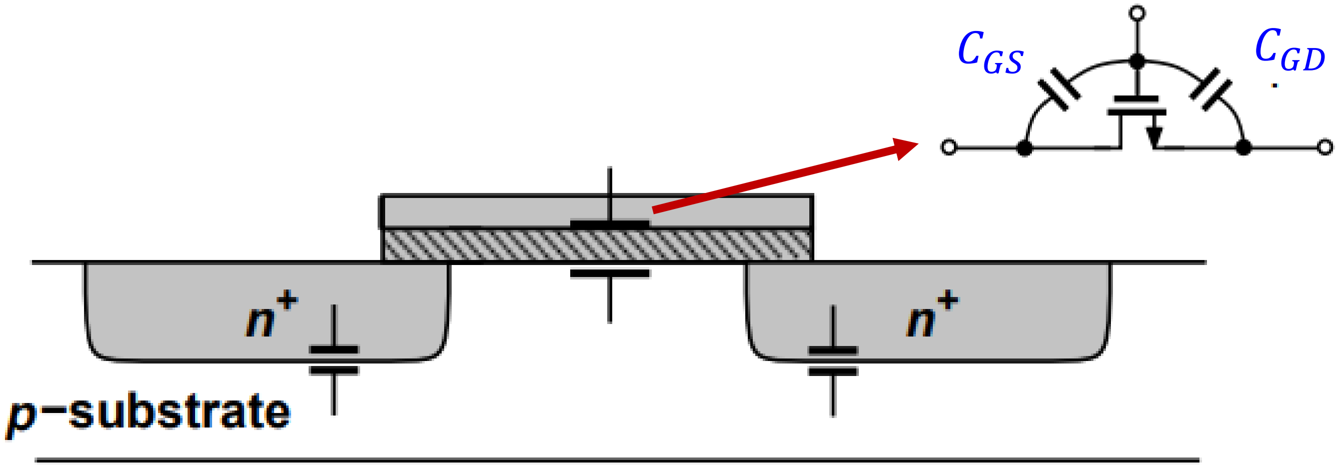


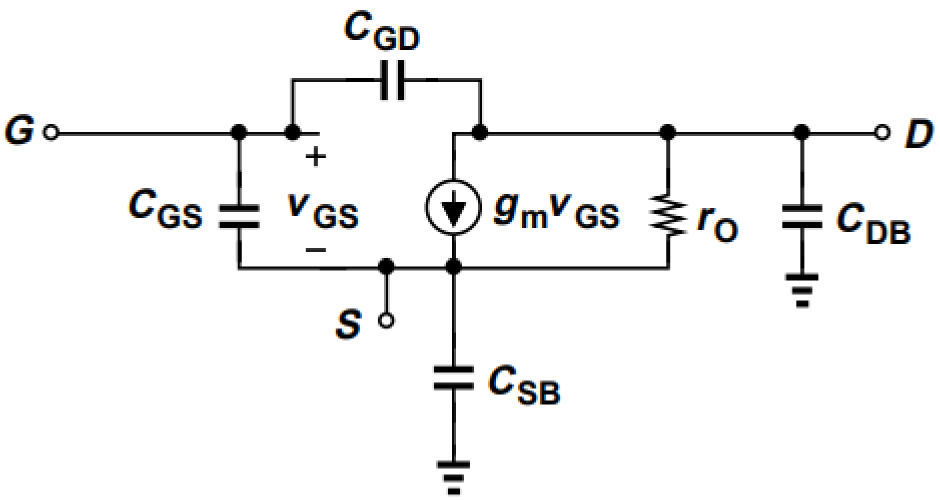
(a) Structure of an integrated bipolar transistor, (b) small-signal model including collector-substrate capacitance, (c) device symbol with capacitances shown explicitly.

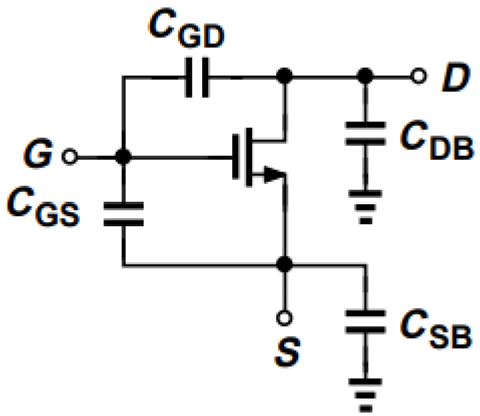
Example : identify all of the capacitances



High-frequency models of MOSFET







Quiz: identify all of the capacitances