Integrated Circuit Design

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Chapter 3: ANALOG CMOS CIRCUITS

Outline

- Basic CMOS amplifier
- MOSFET Cascode Stage
- MOSFET Current Mirror
- MOSFET Differential Amplifiers

Basic CMOS amplifier

MOSFET Amplifier Design

A MOSFET amplifier circuit should be designed to ensure that the MOSFET operates in the saturation region, allow the desired level of DC current to flow, and couple to a small-signal input source and to an output "load".

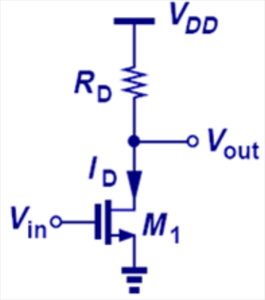
Proper "DC biasing" is required! *(DC analysis using large-signal MOSFET model)*

MOSFET Amplifier Design

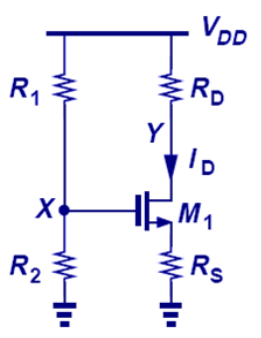
Key amplifier parameters: *(AC analysis using small-signal MOSFET model)*

- **Voltage gain** $A_v = v_{out}/v_{in}$.
- **Input resistance** R_{in}: resistance seen between the input node and ground (with output terminal floating).
- **Output resistance** R_{out}: resistance seen between the output node and ground (with input terminal grounded).

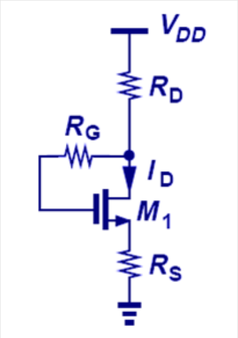
MOSFET biasing



Mạch khuếch đại chế độ B

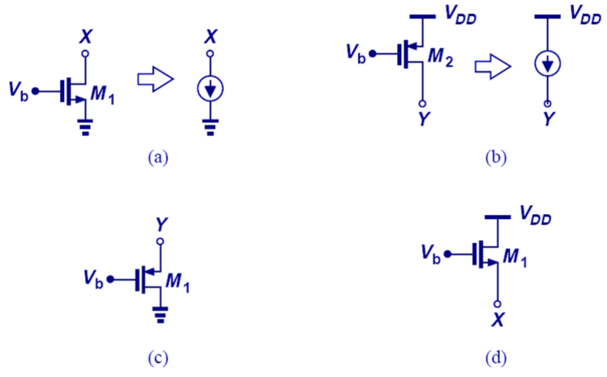


Mạch khuếch đại chế độ A



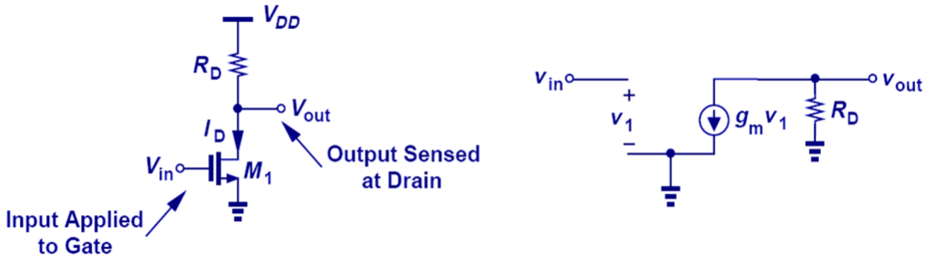
MOSFETs as Current Sources

A MOSFET behaves as a current source when it is operating in the saturation region.
An NMOSFET draws current from a point to ground (“sinks current”), whereas a PMOSFET draws current from VDD to a point (“sources current”).



Common-Source Stage

Common-Source Stage: $\lambda = 0$

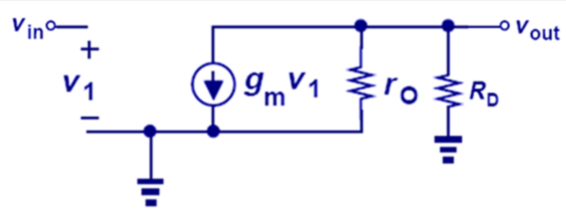


$$A_v = -g_m R_D = -\sqrt{2\mu_n C_{ox} \frac{W}{L} I_D} R_D$$

$$R_{in} = \infty$$

$$R_{out} = R_D$$

Common-Source Stage: $\lambda \neq 0$

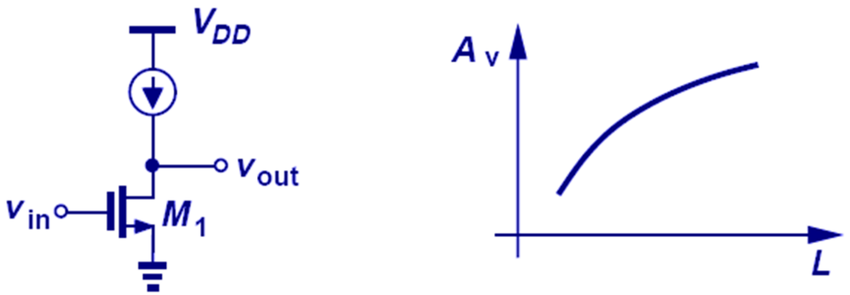


$$A_v = -g_m (R_D \parallel r_O)$$

$$R_{in} = \infty$$

$$R_{out} = R_D \parallel r_O$$

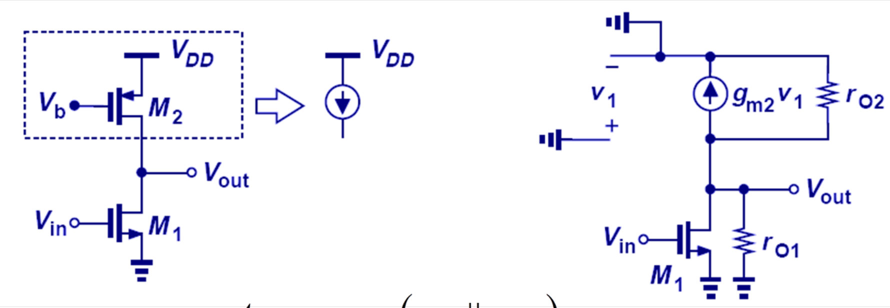
CS Gain Variation with L



$$|A_v| = g_m r_o = \frac{\sqrt{2\mu_n C_{ox} \frac{W}{L} I_D}}{\lambda I_D} \propto \sqrt{\frac{2\mu_n C_{ox} WL}{I_D}}$$

CS Stage with Current-Source PMOS Load

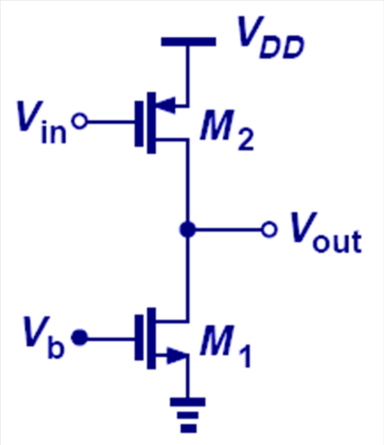
Recall that a PMOSFET can be used as a current source from V_{DD}.
Use a PMOSFET as a load of an NMOSFET CS amplifier.



$$A_v = -g_{m1}\left(r_{O1} \parallel r_{O2}\right)$$

$$R_{out} = r_{O1} \parallel r_{O2}$$

PMOS CS Stage with NMOS Load

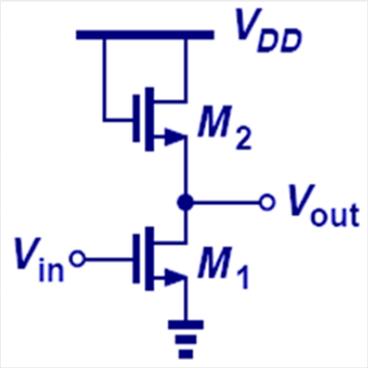


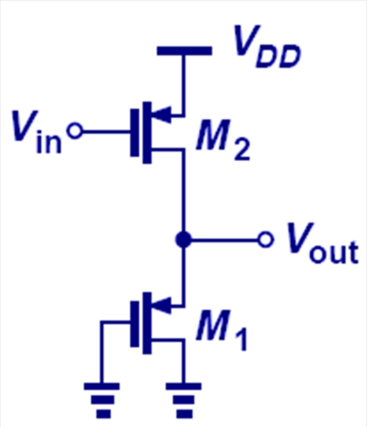
$$A_v = -g_{m2}(r_{O1} \parallel r_{O2})$$

$$R_{out} = r_{O1} \parallel r_{O2}$$

CS Stage with Diode-Connected Load

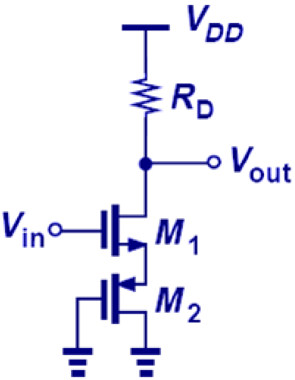
$A_v = ?$ $R_{out} = ?$

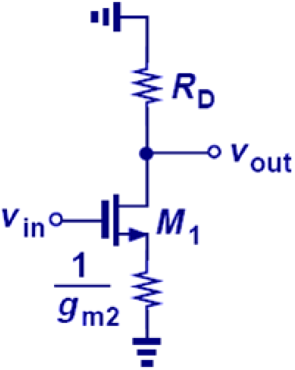




Problem 1

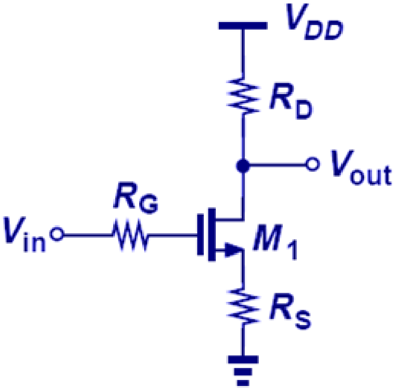
$A_v = ?$





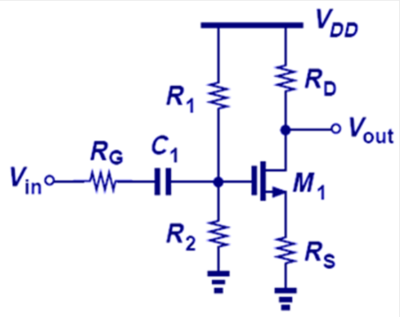
Problem 2

$A_v = ?$

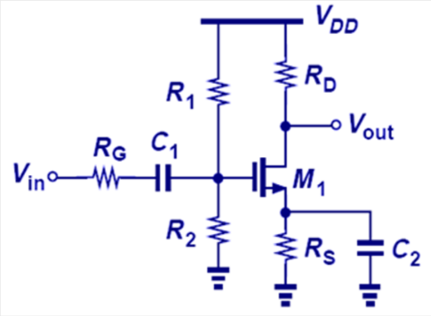


Problem 3

$A_v = ?$



V_{DD}
R_1
R_D
V_{out}
R_G
C_1
V_{in}
M_1
R_2
R_S

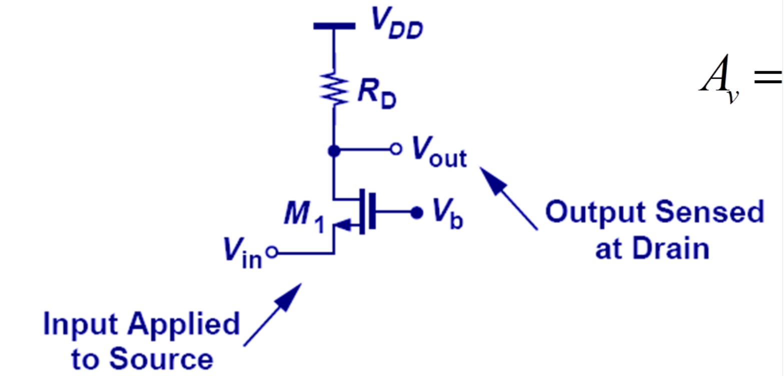


V_{DD}
R_D
R_1
V_{out}
R_G
C_1
V_{in}
M_1
R_2
R_S
C_2

Common-gate Stage

Common-Gate Amplifier Stage

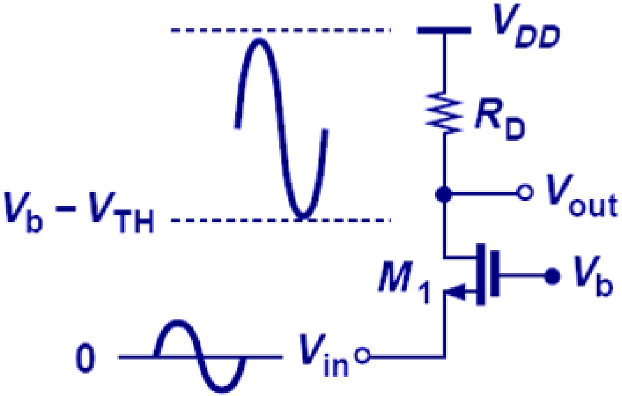
An increase in V_{in} decreases V_{GS} and hence decreases I_D.
The voltage drop across R_D decreases $\Rightarrow$ V_{out} increases.
The small-signal voltage gain (A_v) is positive.



$$A_v = g_m R_D$$

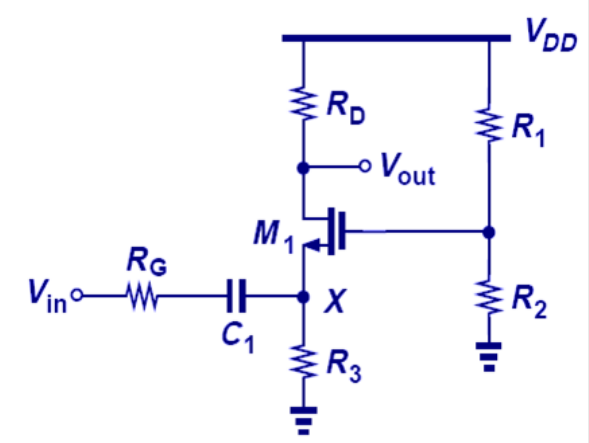
CG: Operation in Saturation Region

For M_1 to operate in saturation, V_{out} cannot fall below $V_b - V_{TH}$. $\Rightarrow$ Trade-off between headroom and voltage gain.



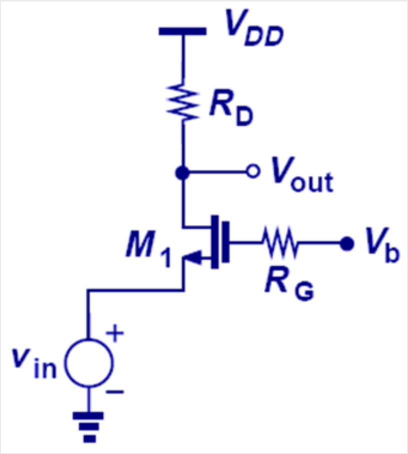
Problem 1

$A_v = ?$



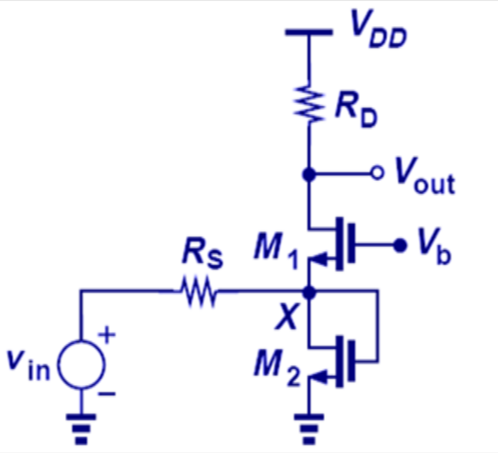
Problem 2

$A_v = ?$



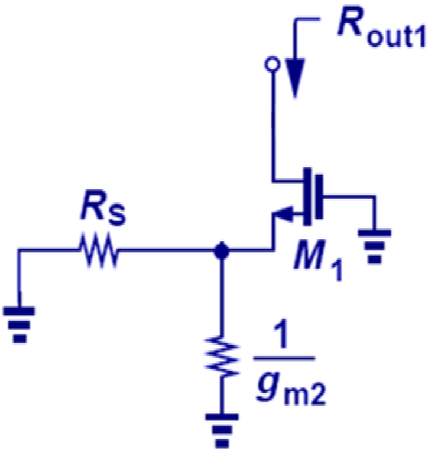
Problem 3

$A_v = ?$



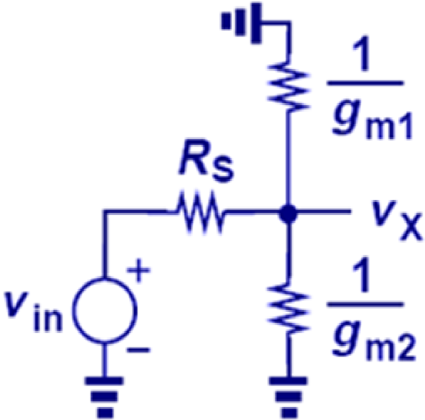
Problem 4

$A_v = ?$



Problem 5

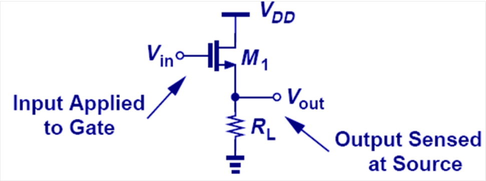
$A_v = ?$

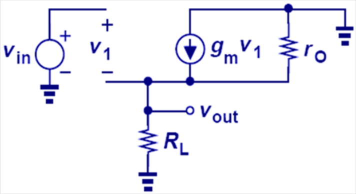


Source Follower Stage

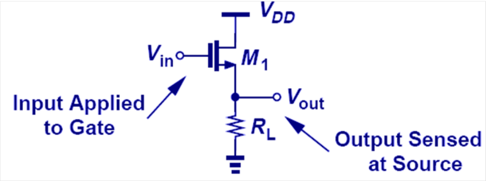
Source Follower Stage

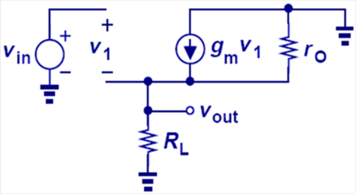
Amplifier Circuit and Small-signal analysis circuit for determining voltage gain, A_v.





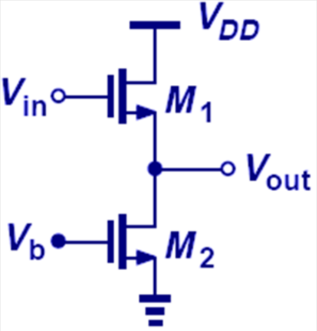
Amplifier Circuit and Small-signal analysis circuit for determining voltage gain, A_v.





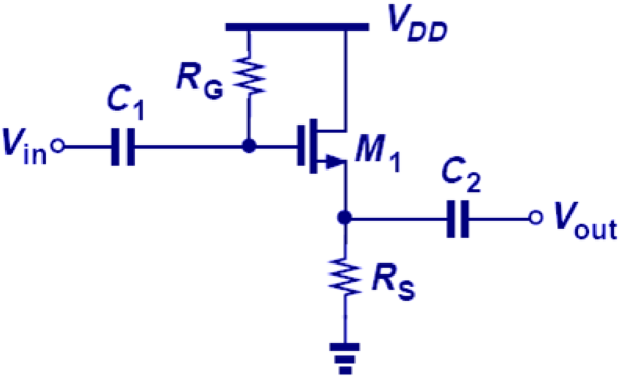
Example

M2 acts as a current source.



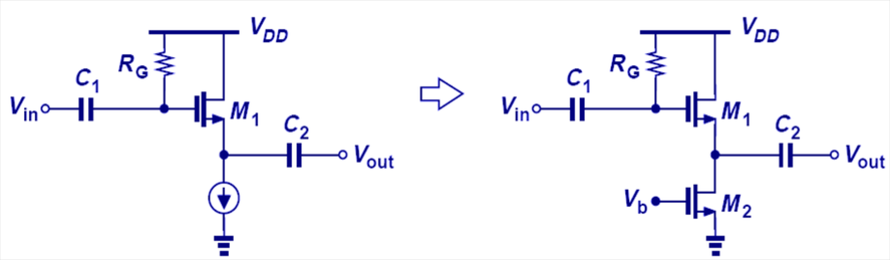
Source Follower with Biasing

R_G sets the gate voltage to V_{DD}; R_S sets the drain current.



Supply-Independent Biasing

If R_s is replaced by a current source, the drain current I_D becomes independent of the supply voltage V_{DD}.



Comparison of Amplifier Topologies

Common Source

- **Large $A_v < 0$**
  - degraded by R_S
- **Large R_{in}**
  - determined by biasing circuitry
- $R_{out} \cong R_D$
- **r_o decreases A_v & R_{out}**
  but impedance seen looking into the drain can be “boosted” by source degeneration

Common Gate

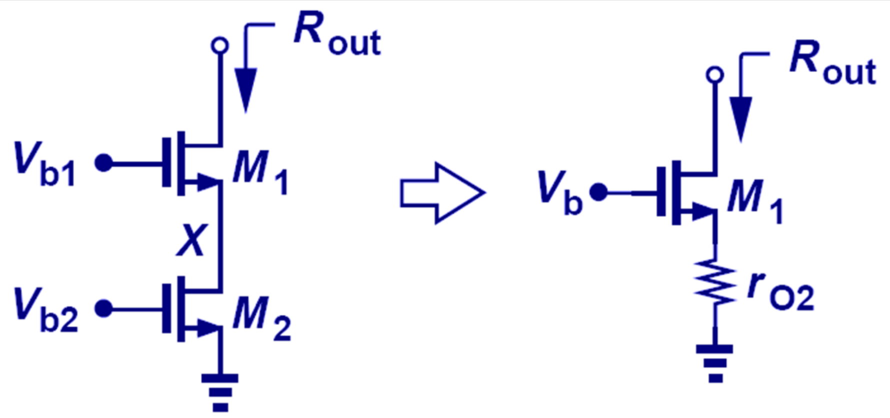
- **Large $A_v > 0$**
  -degraded by R_S
- **Small R_{in}**
  - decreased by R_S
- $R_{out} \cong R_D$
- **r_o decreases A_v & R_{out}**
  but impedance seen looking into the drain can be “boosted” by source degeneration

Source Follower

- **$0 < A_v \leq 1$**
- **Large R_{in}**
  - determined by biasing circuitry
- **Small R_{out}**
  - decreased by R_S
- **r_o decreases A_v & R_{out}**

MOS Cascode Amplifier

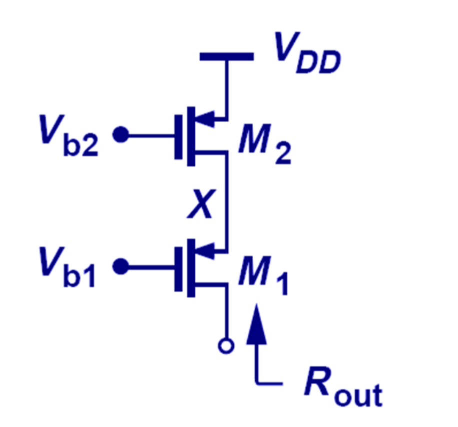
NMOS Cascode Stage



$$R_{out} = \left(1 + g_{m1} r_{O1}\right) r_{O2} + r_{O1}$$

$$R_{out} \approx g_{m1} r_{O1} r_{O2}$$

PMOS Cascode Stage

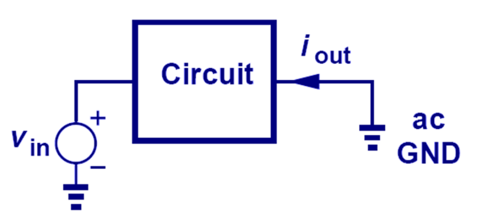


$$R_{out} = (1 + g_{m1} r_{O1}) r_{O2} + r_{O1}$$

$$R_{out} \approx g_{m1} r_{O1} r_{O2}$$

Short-Circuit Transconductance

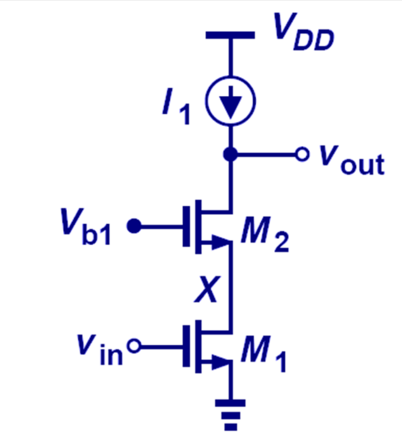
The short-circuit transconductance is a measure of the strength of a circuit in converting an input voltage signal into an output current signal:



$$G_m \equiv \left. \frac{i_{out}}{v_{in}} \right|_{v_{out}=0}$$

$$A_v = -G_m R_{out}$$

MOS Cascode Amplifier



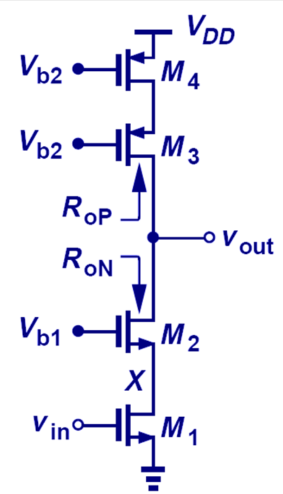
$$A_v = -G_m R_{out}$$

$$A_v \approx -g_{m1}\left[(1+g_{m2}r_{O2})r_{O1}+r_{O2}\right]$$

$$A_v \approx -g_{m1}r_{O1}g_{m2}r_{O2}$$

PMOS Cascode Current Source as Load

A large load impedance can be achieved by using a PMOS cascode current source.



$$R_{oN} \approx g_{m2} r_{O2} r_{O1}$$

$$R_{oP} \approx g_{m3} r_{O3} r_{O4}$$

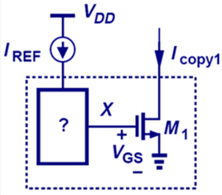
$$R_{out} = R_{oN} \,||\, R_{oP}$$

MOS Current Mirror

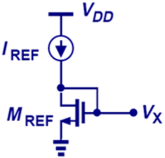
MOS Current Mirror

The motivation behind a current mirror is to duplicate a (scaled version of the) “golden current” to other locations.

Current mirror concept



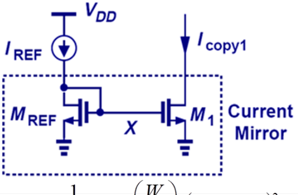
Generation of required V_{GS}



$$I_{REF} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_{REF}(V_X - V_{TH})^2$$

$$V_X = \sqrt{\frac{2I_{REF}}{\mu_n C_{ox}(W/L)_1}} + V_{TH1}$$

Current Mirror Circuitry

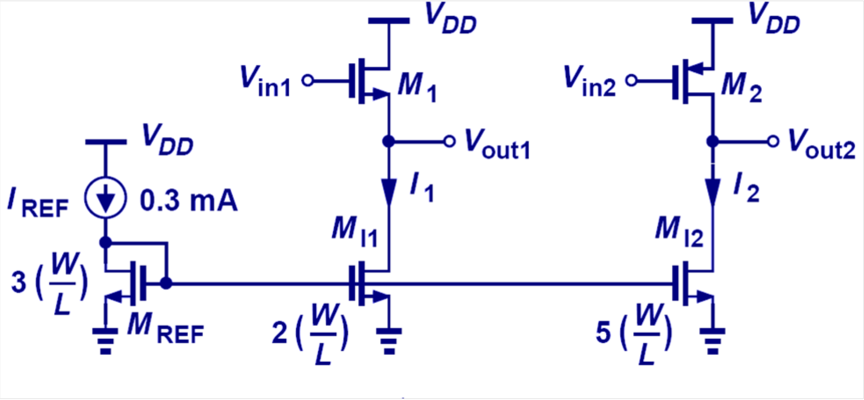


$$I_{copy1} = \frac{1}{2}\mu_n C_{ox}\left(\frac{W}{L}\right)_1(V_X - V_{TH})^2$$

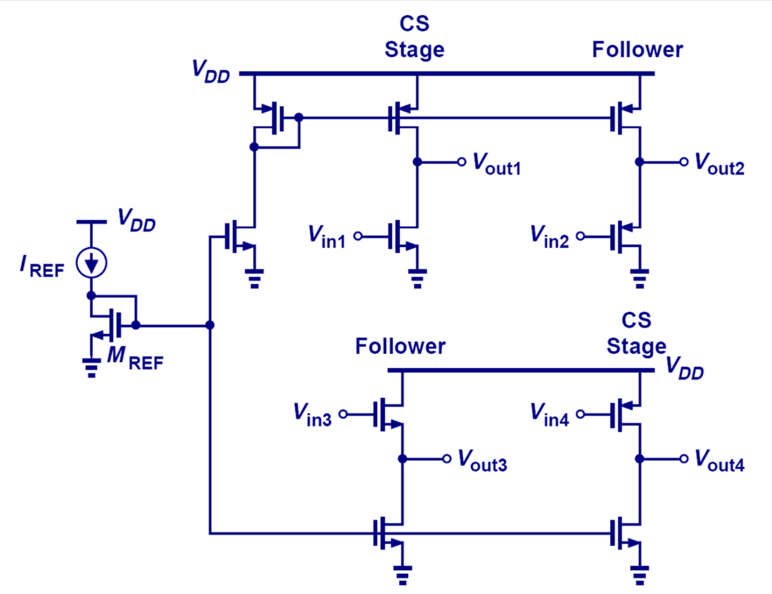
$$\boxed{I_{copy1} = \frac{(W/L)_1}{(W/L)_{REF}} I_{REF}}$$

Example: Current Scaling

MOS current mirrors can be used to scale I_{REF} up or down.



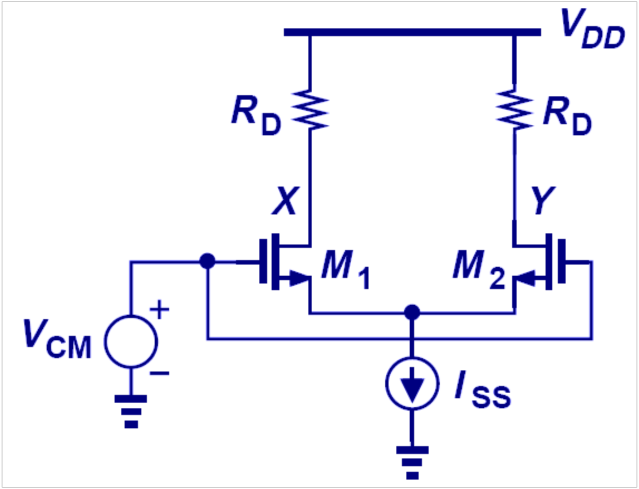
CMOS Current Mirror



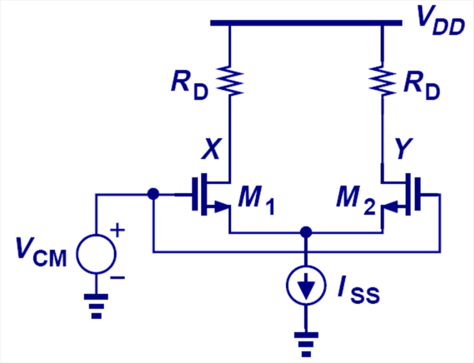
MOSFET Differential Amplifiers

Common-Mode (CM) Response

A MOSFET differential pair produces zero differential output as V_{CM} changes.



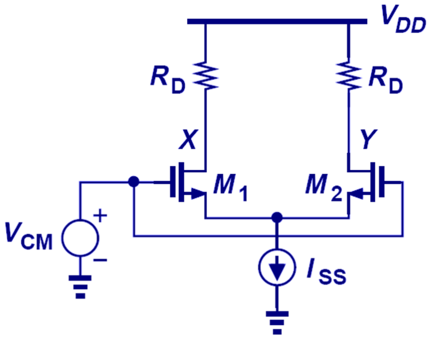
The equilibrium overdrive voltage is defined as $V_{GS} - V_{TH}$ when M_1 and M_2 each carry a current of $I_{SS}/2$.



$$(V_{GS} - V_{TH})_{equil} = \sqrt{\frac{I_{SS}}{\mu_n C_{ox} \frac{W}{L}}}$$

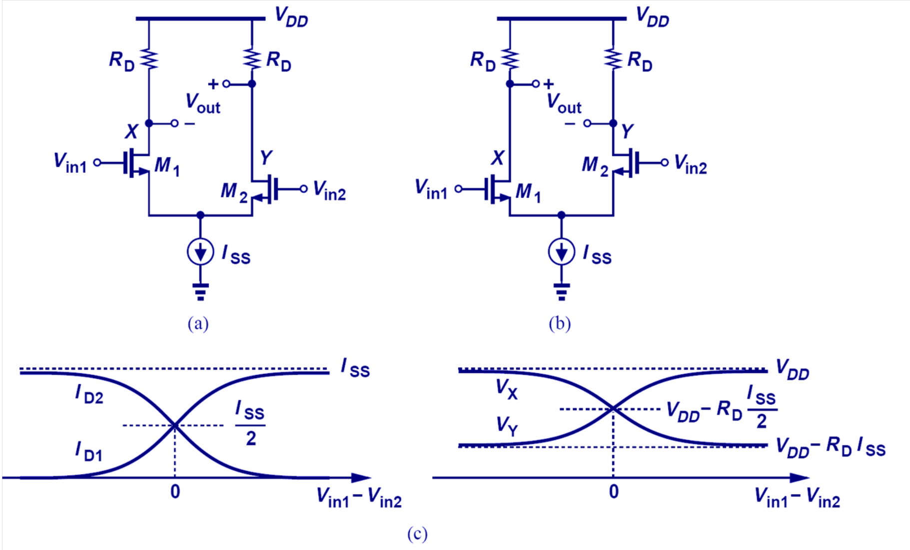
Minimum CM Output Voltage

In order to maintain M_1 and M_2 in saturation, the common-mode output voltage cannot fall below $V_{CM} - V_{TH}$.

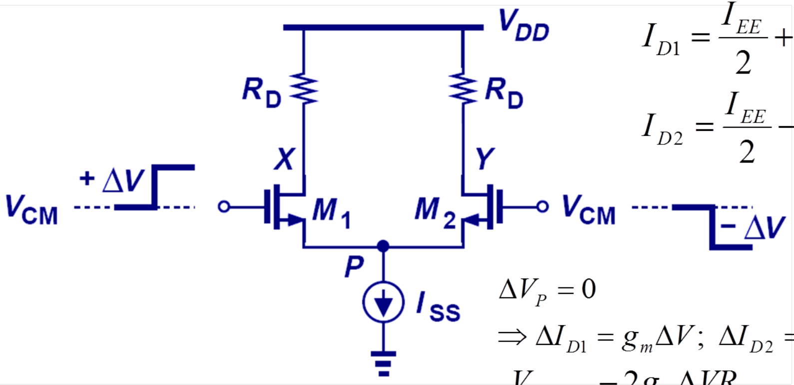


$$V_{DD} - R_D \frac{I_{SS}}{2} > V_{CM} - V_{TH}$$

Differential Response



Small-Signal Response



$$I_{D1} = \frac{I_{EE}}{2} + \Delta I$$

$$I_{D2} = \frac{I_{EE}}{2} - \Delta I$$

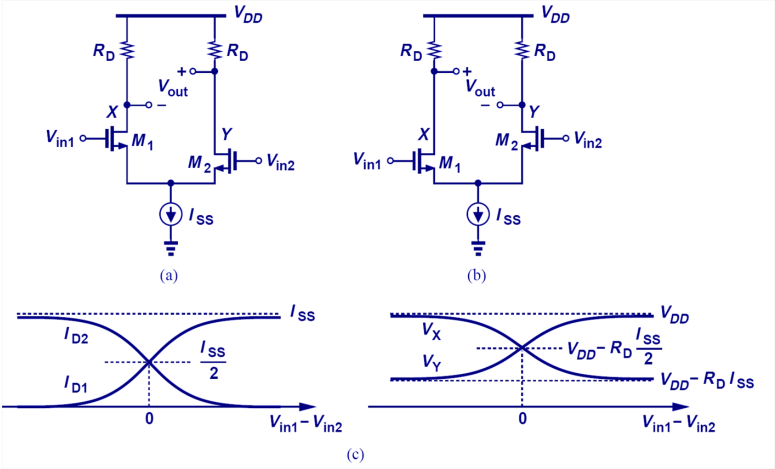
$$\Delta V_P = 0$$

$$\Rightarrow \Delta I_{D1} = g_m \Delta V; \;\; \Delta I_{D2} = -g_m \Delta V$$

$$A_v = \frac{V_{out}}{V_{in}} = \frac{-2g_m \Delta V R_D}{2\Delta V} = -g_m R_D$$

Maximum Differential Input Voltage

There exists a finite differential input voltage that completely steers the tail current from one transistor to the other. This value is known as the maximum differential input voltage.



next .... **Chapter 4: DIGITAL CMOS CIRCUITS**