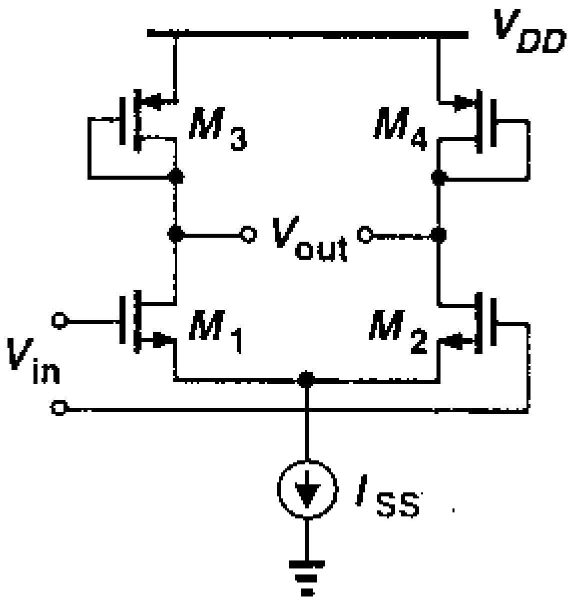
Lecture – 16

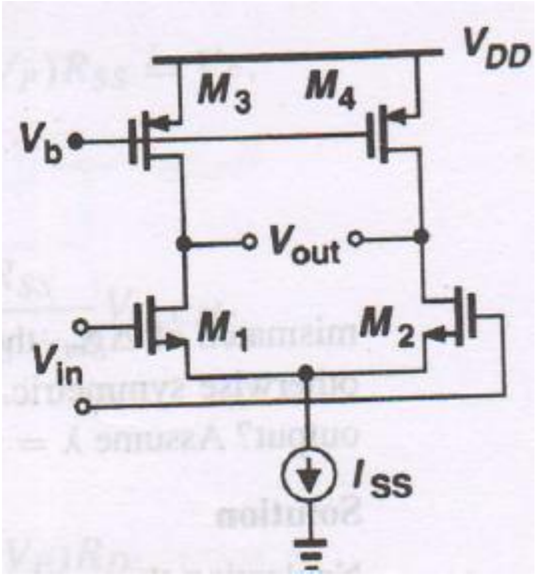
Date: 12.10.2015

- Differential Pair with Active Load
- Differential Pair with Current Mirror
- Gilbert Cell

Differential Amplifier with Active Load

- By now we know, the load resistors in differential pair can be replaced by diode-connected or source-connected loads
- It can help in mitigating the common-mode to differential conversion arising out from R_D mismatch



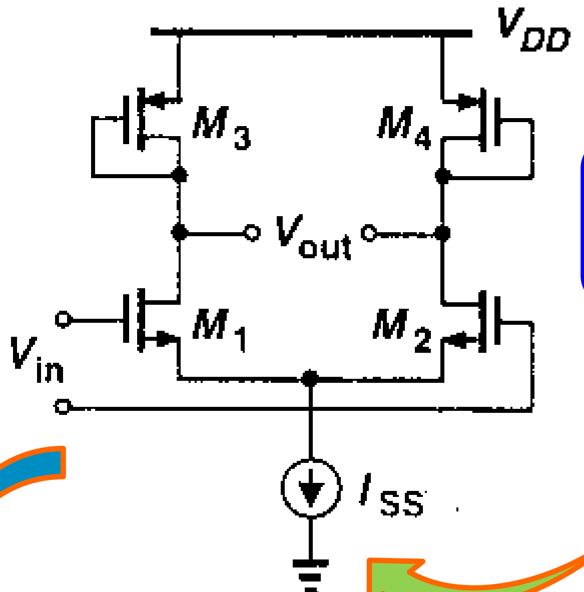


Its easier to define output CM level as M_3/M_4 are in saturation by default

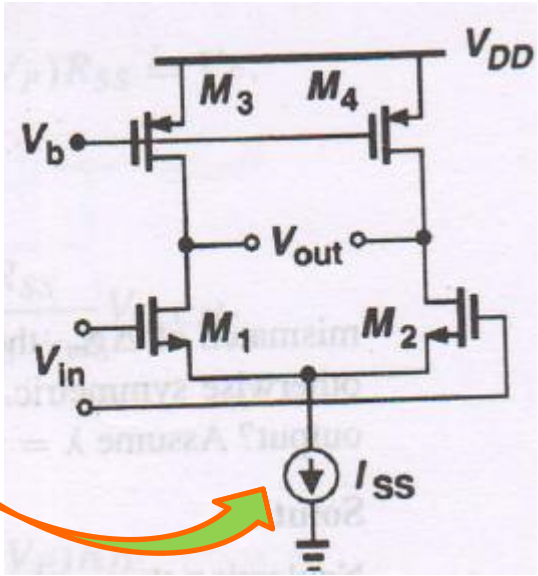
M_3/M_4 are not in saturation by default & therefore output CM level not well defined

Differential Pair with Active Load

- **Using half-circuit approach:**



Differential pair with ideal current source



$$A_v = -g_{mN}\left(g_{mP}^{-1} \parallel r_{oN} \parallel r_{oP}\right)$$

$$A_v = -g_{mN}\left(r_{oN} \parallel r_{oP}\right)$$

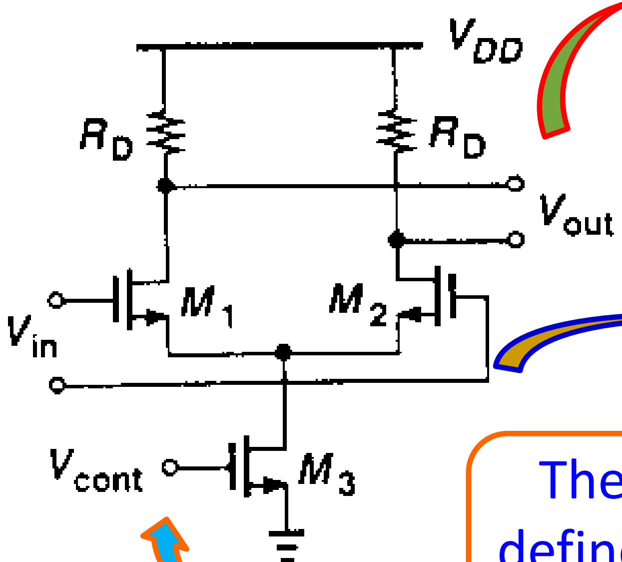
$$\therefore A_v \approx -\frac{g_{mN}}{g_{mP}} = -\sqrt{\frac{\mu_n (W/L)_N}{\mu_P (W/L)_P}}$$

Gilbert Cell

Two important aspects of differential pair

- **small signal gain is function of tail current**
- **the whole tail current can be steered to one of two paths by some means**

- **These features can be utilized to design very interesting and useful circuit known as Gilbert Cell [a differential pair whose gain can be varied by control voltage]**



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

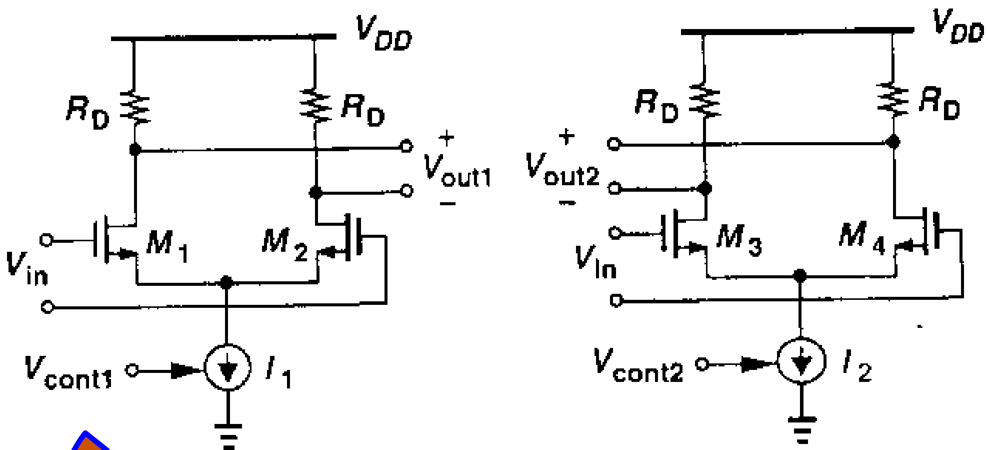
Varies from ZERO (if ID_3=0) to a limit set by the voltage headroom and device dimensions

The control voltage defines the tail current and hence the gain

Simple Variable Gain Amplifier (VGA)

Gilbert Cell (contd.)

- Suppose we require an amplifier whose gain can be continuously varied from a NEGATIVE value to a POSITIVE value.
- Definitely, two VGA with opposite gains.



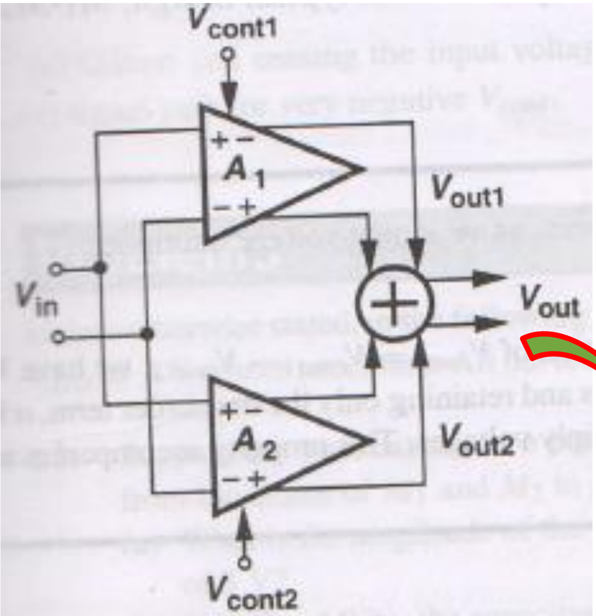
This pair of VGA should be designed in such a way that they give opposite gains

$V_{out1}/V_{in} = -g_m R_D$ and $V_{out2}/V_{in} = +g_m R_D$ ↔ require variation of I_1 and I_2 in opposite directions

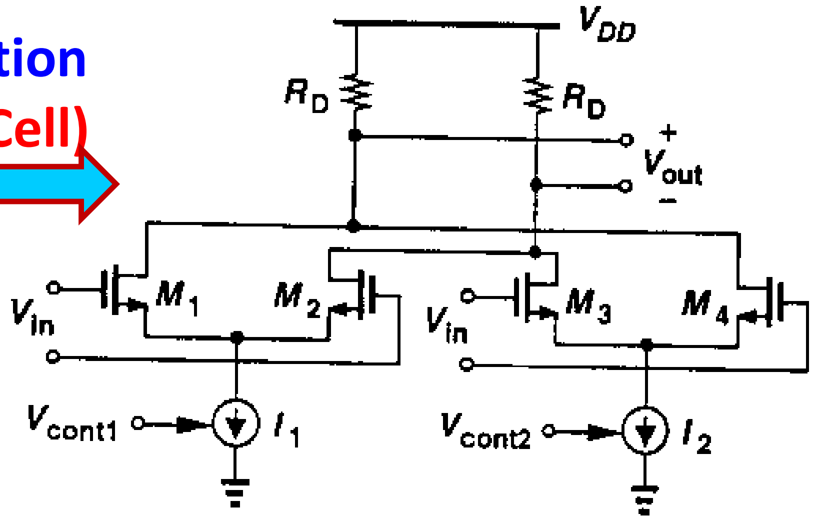
How to combine V_{out1} and V_{out2} in a single output?

Gilbert Cell (contd.)

How to combine V_{out1} and V_{out2} in a single output?



Actual Implementation (i.e, Gilbert Cell)



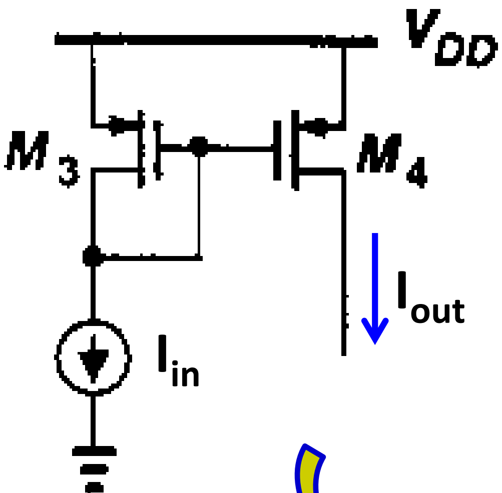
$$V_{out} = V_{out1} + V_{out2} = A_1 V_{in} + A_2 V_{in}$$

A_1 and A_2 controlled by V_{cont1} and V_{cont2} respectively

Here, instead of adding V_{out1} and V_{out2}, the drain terminals are shorted to sum the currents and subsequently generate the output voltage

Active Current Mirror

- We know: CM can also process signals i.e, operate as "active" elements

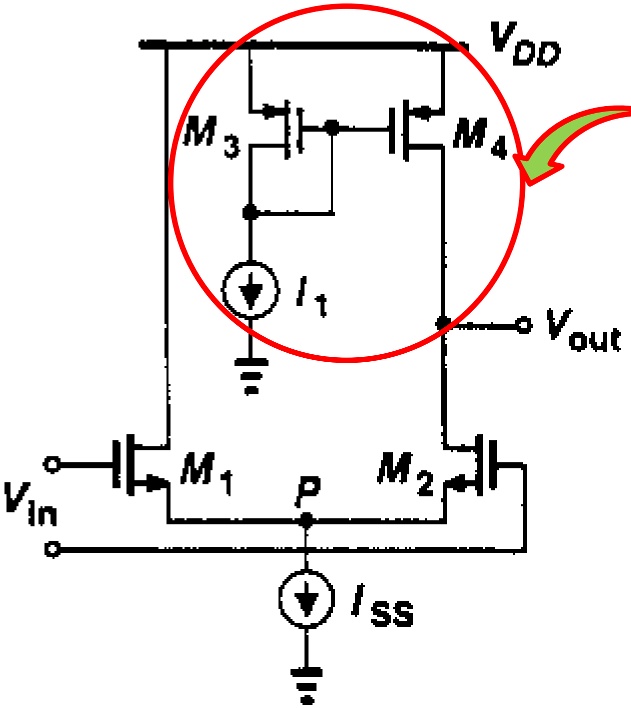


Here, $I_{out} = I_{in}$ if we assume M_1 and M_2 are identical and $\lambda = 0$

With the direction shown, this circuits performs no inversion → for small signal point of view, if I_{in} increases by ΔI then I_{out} also increases by ΔI

Active Current Mirror (contd.)

- Now, let us consider following configuration in which a differential amplifier is loaded with a CM and the output is single ended

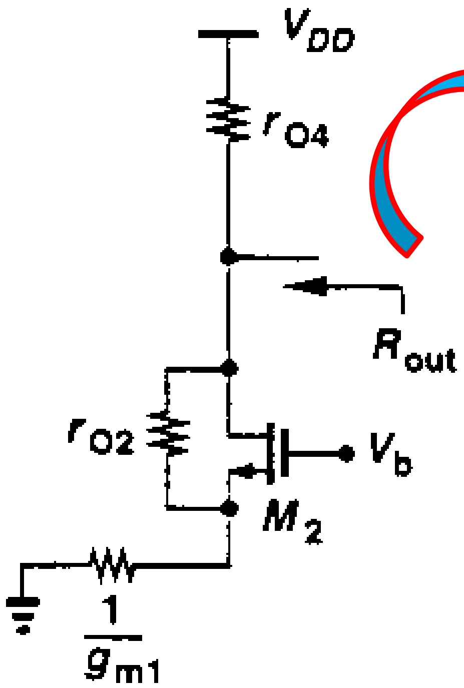


Current Mirror

$$G_m = \frac{I_{in}}{V_{in}} = \frac{\left(g_{m1}V_{in}\right)/2}{V_{in}} = \frac{g_{m1}}{2}$$

Active Current Mirror (contd.)

- For output impedance, the circuit can be simplified into following:



$$R_{out} = \left(\left(1 + g_{m2} r_{o2}\right)\left(\frac{1}{g_{m1}}\right) + r_{o2} \right) \| r_{o4} \approx \left(\frac{1}{g_{m1}} + 2r_{o2}\right) \| r_{o4} \approx 2r_{o2} \| r_{o4}$$

$$\therefore A_v = G_m R_{out} \approx \frac{g_{m1}}{2}\left(2r_{o2} \| r_{o4}\right)$$

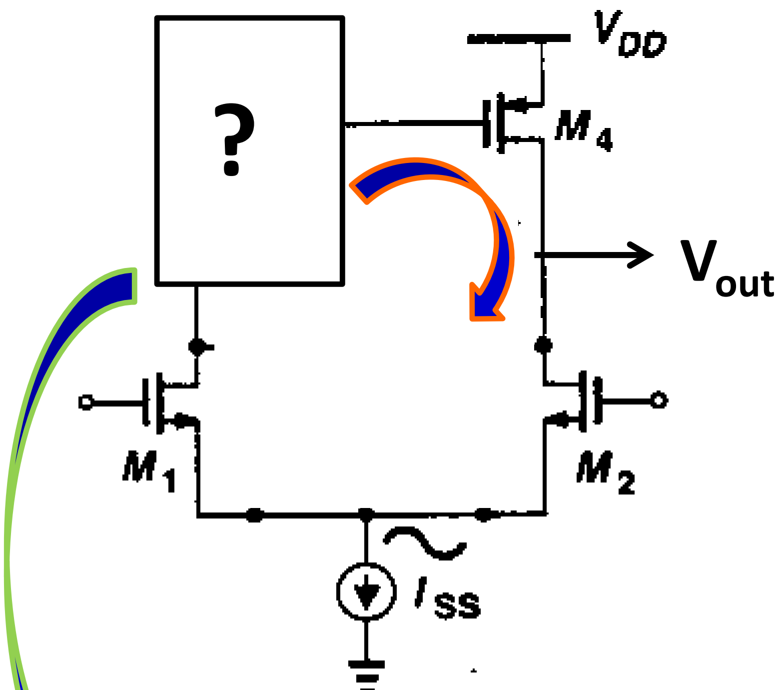
Smaller than a simple differential pair

If $r_{o4} \to \infty$, then $A_v \to g_{m1} r_{o2}$

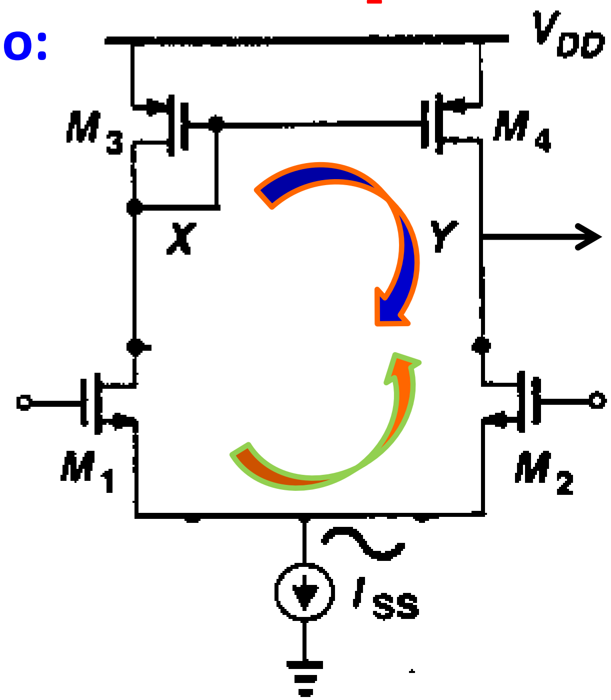
In this configuration, the small-signal drain current of M_1 is wasted → this is partly responsible for reduction in gain

Active Current Mirror (contd.)

- Therefore it is desirable to utilize the drain current of M_1 to enhance A_v
- Following configuration depicts a scenario:



This block has to be designed to provide the required functionality

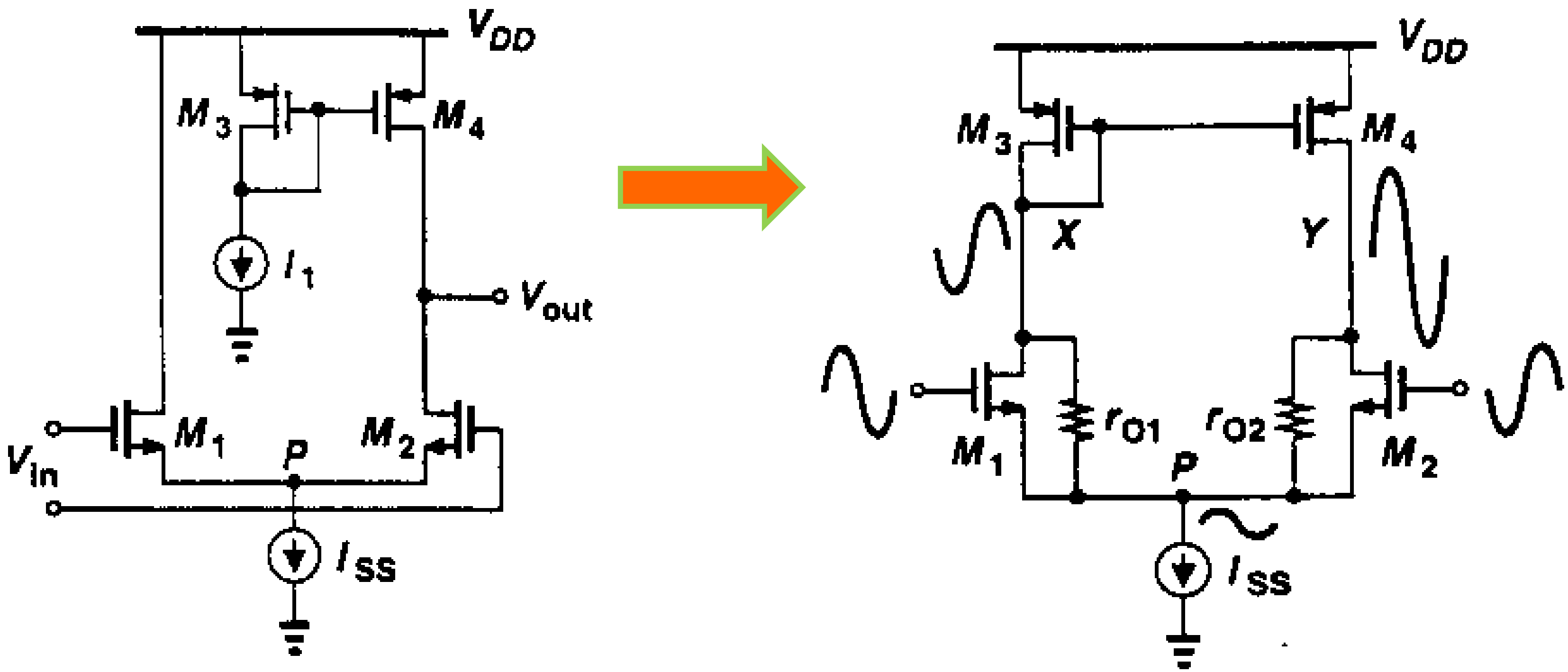


To see how M3 enhances the gain

Suppose V_{G1} increases by small amount → leads to increase in I_{D1} by ΔI and decrease in I_{D2} by ΔI → I_{D3} and I_{D4} increases by ΔI and decreases the V_{DS} of M_2 → increases V_{out} → active current mirror functionality

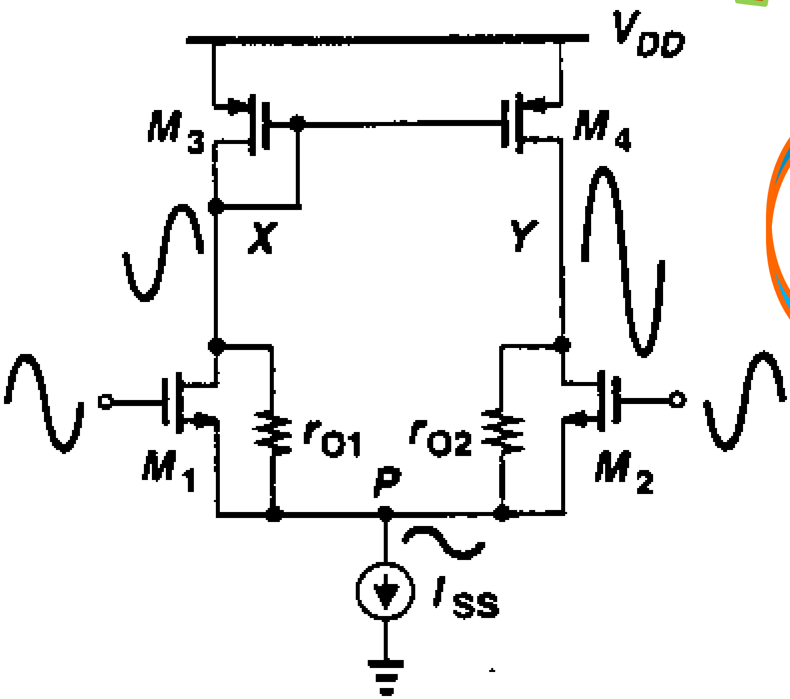
Active Current Mirror (contd.)

Combine Drain Currents to Enhance Gain



Active Current Mirror (contd.)

Small Signal Analysis



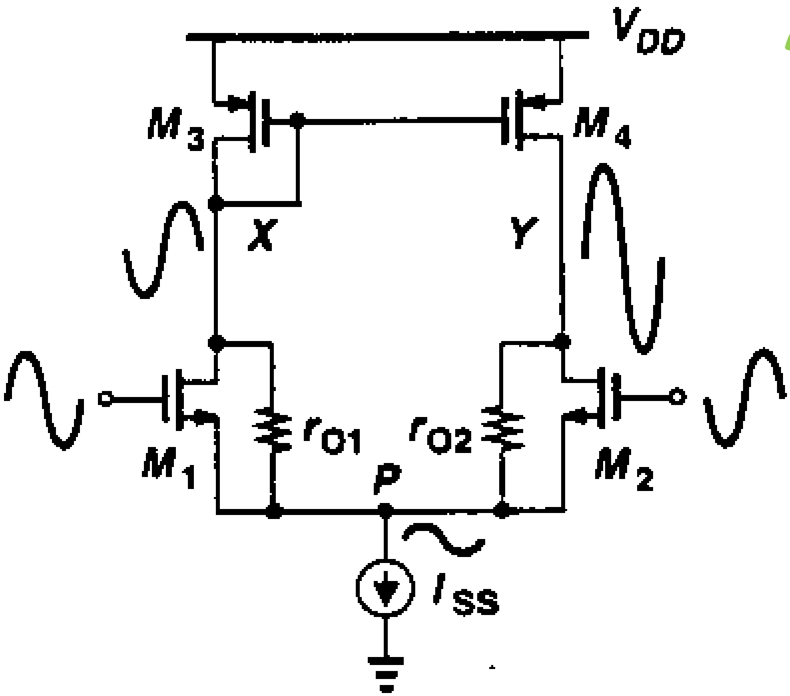
The voltage swings at both X and Y nodes are different

Because the diode-connected M_3 yields a much lower gain from the input to node X as compared to gain from input to node Y

The effects of V_X and V_Y are different at node P ↔ therefore the node P isn't really ac-grounded

Active Current Mirror (contd.)

Small Signal Analysis

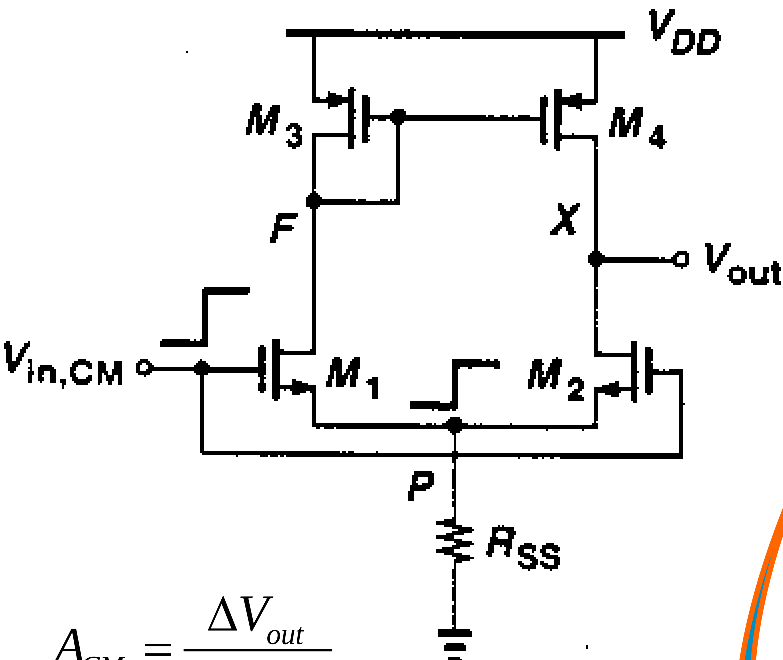


$$\therefore A_v = g_{m1}\left(r_{o2} \| r_{o4}\right)$$

Higher than the earlier circuit

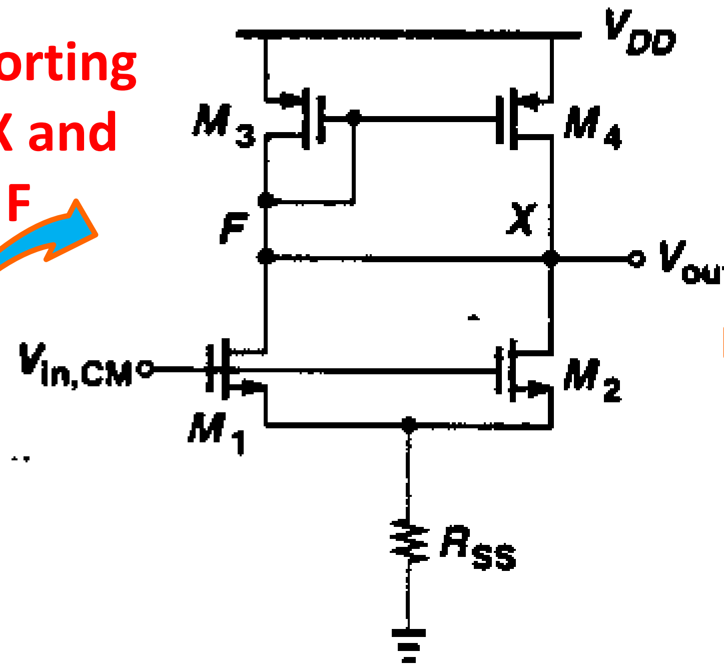
Active Current Mirror (contd.)

Common Mode Analysis



$$A_{CM} = \frac{\Delta V_{out}}{\Delta V_{in,CM}}$$

Allows shorting of node X and node F

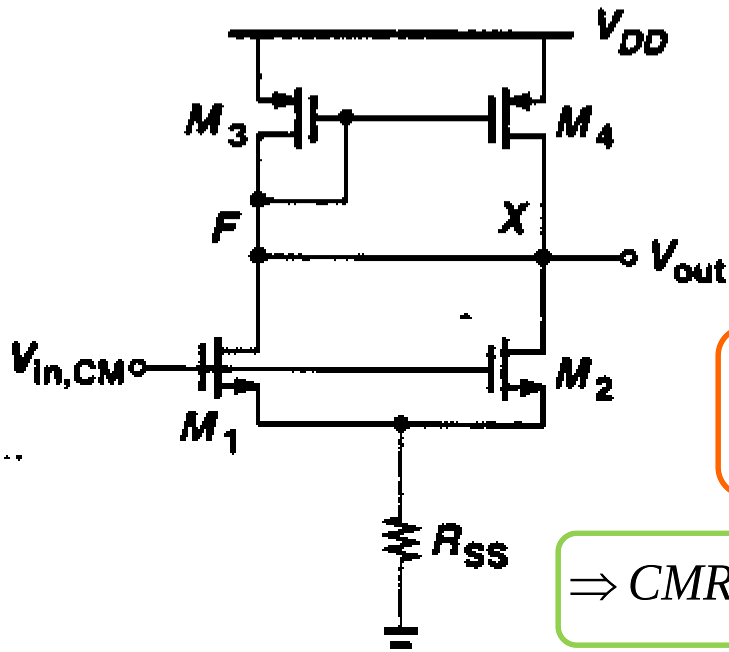


With perfect symmetry $V_{X,DC}=V_{F,DC}$

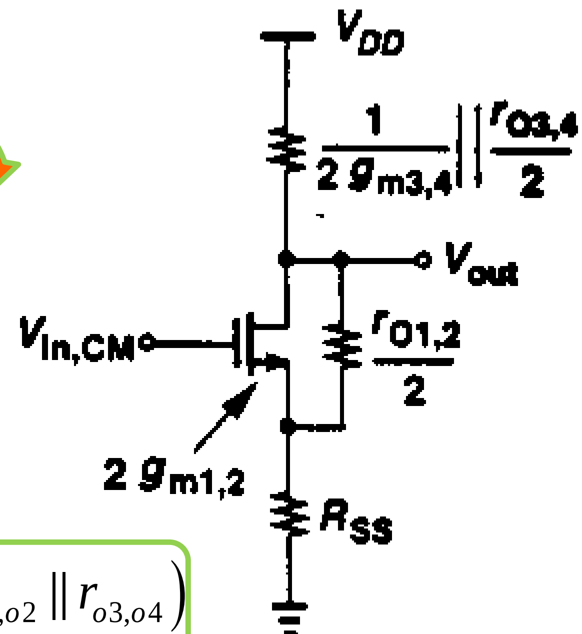
This is for any input CM level. For example, as $V_{in,CM}$ increases, V_F drops and so does V_{out}

Active Current Mirror (contd.)

Common Mode Analysis



Equivalent Circuit



$$A_{CM} = \frac{-1}{1+2g_{m1,2}R_{SS}}\frac{g_{m1,2}}{g_{m3,4}}$$

$$\Rightarrow CMRR = \left(1+2g_{m1,2}R_{SS}\right)g_{m3,4}\left(r_{o1,o2} \parallel r_{o3,o4}\right)$$

Even with perfect symmetry, the output signal will be corrupted by input CM variations, a drawback that is smaller in fully differential circuits. The problem will be more serious at high frequencies