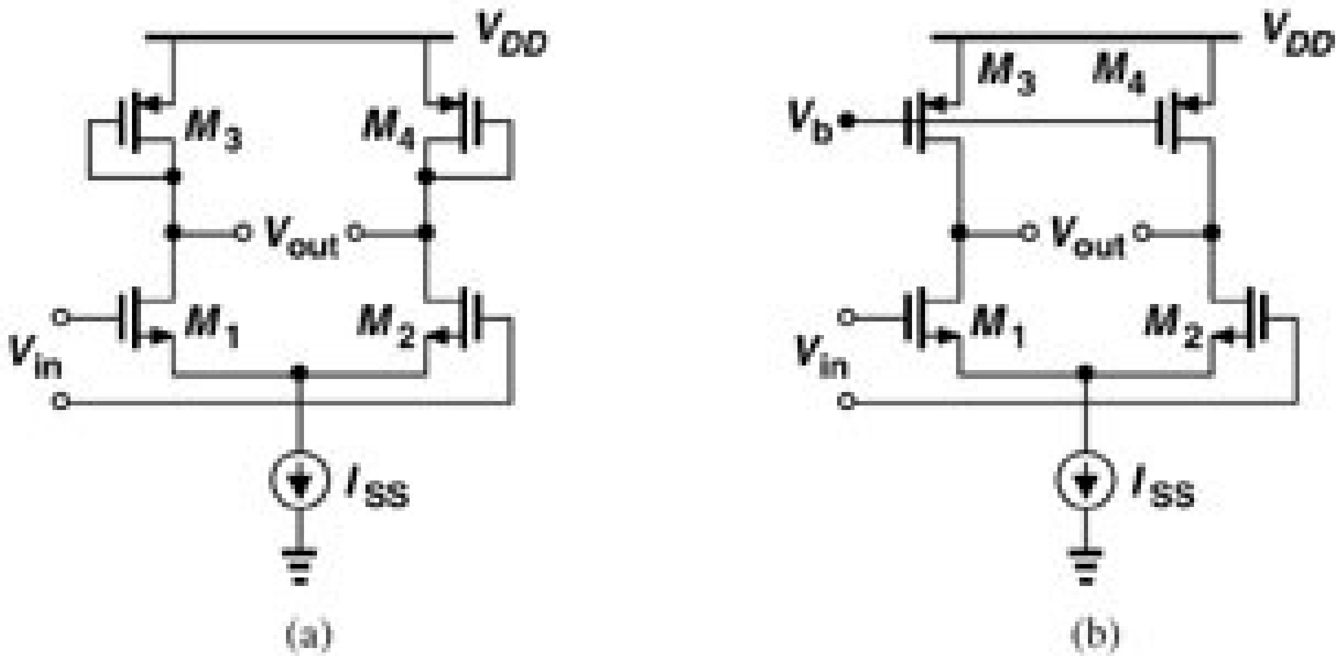
Differential Pair with MOS Loads

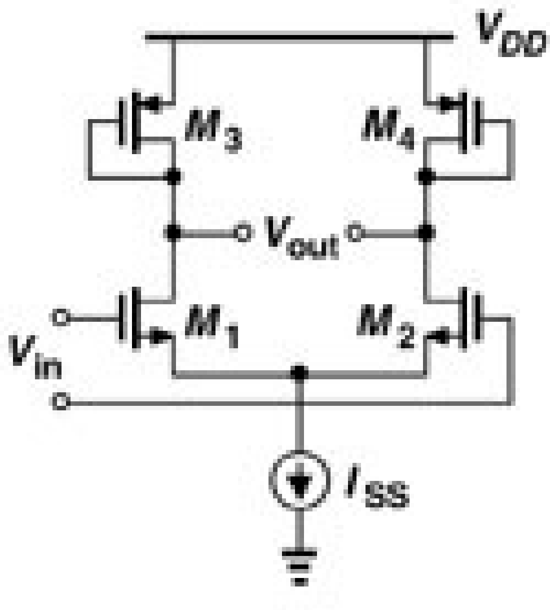
- The load of a differential pair need not be implemented by linear resistors.
- Differential pairs can employed diode-connected or current-source load.

MOS Loads

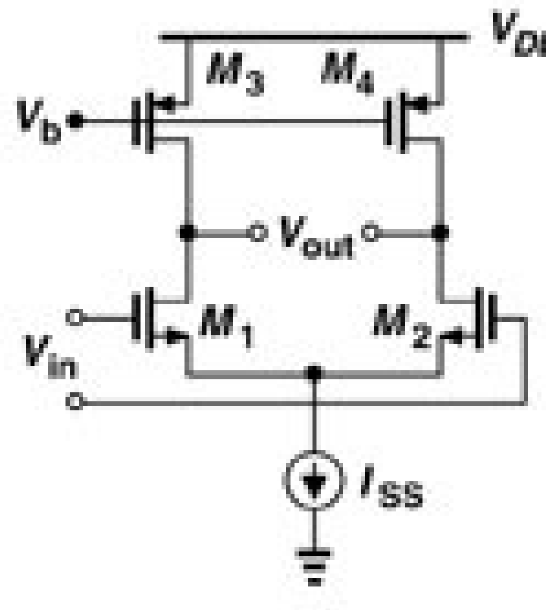


- (a) Diode-connected load
- (b) Current-Source load

MOS Loads: Differential Gain Formulas



(a)



(b)

$$A_{V,diff} = -g_{mN}(g_{mP}^{-1} \parallel r_{oN} \parallel r_{oP})$$

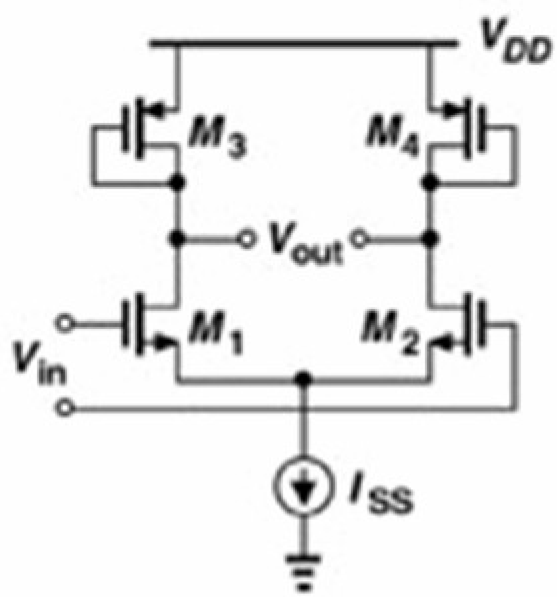
$$\approx -\frac{g_{mN}}{g_{mP}}$$

$$= -\sqrt{\frac{\mu_n (W/L)_N}{\mu_p (W/L)_P}}$$

A

$$A_{V,diff} = -g_{mN}(r_{oN} \parallel r_{oP})$$

B



(a)

- The diode-connected loads consume voltage headroom, thus creating a trade-off between:
  - the output voltage swings,
  - the voltage gain,and
  - the input CM range.
- To achieved higher gain, $(W/L)_p$ must be decreased (from A)

Problem with this approach:

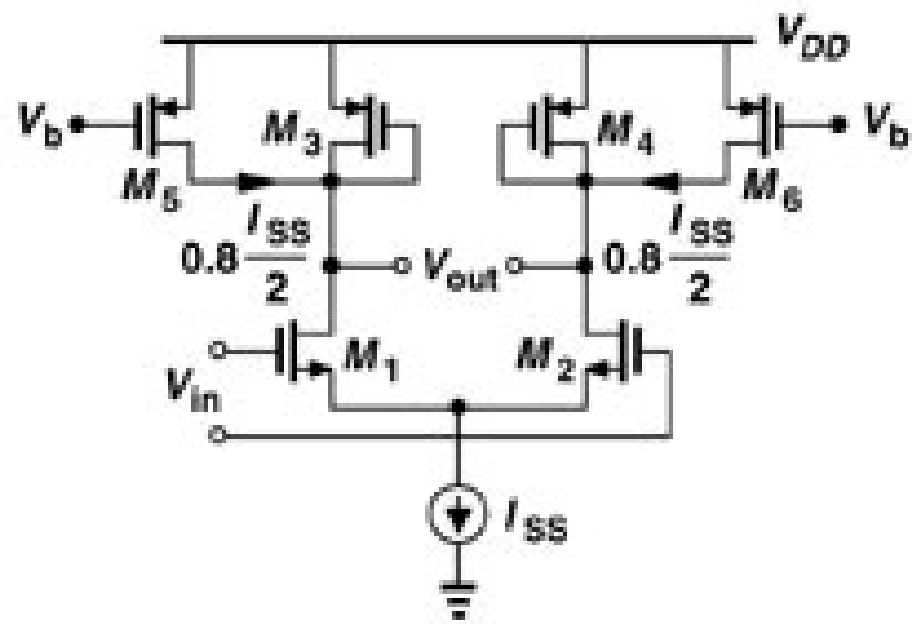
- This increase $|V_{GSP}-V_{THP}|$ and lowering the CM level at nodes X and Y (since more voltage drop across the PMOS).

Overcoming Diode-connected Load swing problem for higher gains:

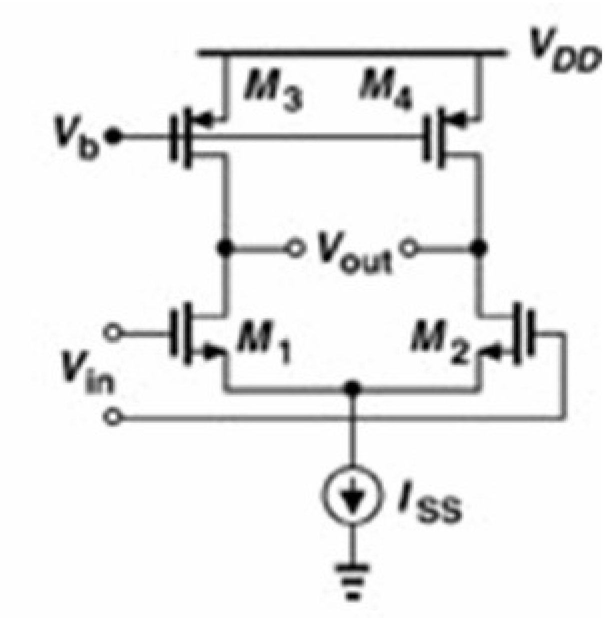
- The idea is to lower the gm of the diode-connected MOS, instead of lowering (W/L)P of load.

Solution:

- If M5 and M6 carry 80% of the drain current of M1 and M2, the current through M3 and M4 is reduced by a factor of 5.
  - → reduce gm for M3 & M4 (instead of lowerring (W/L)p
  - → gain increase by 5



Problems with Current-Source MOS Loads



(b)

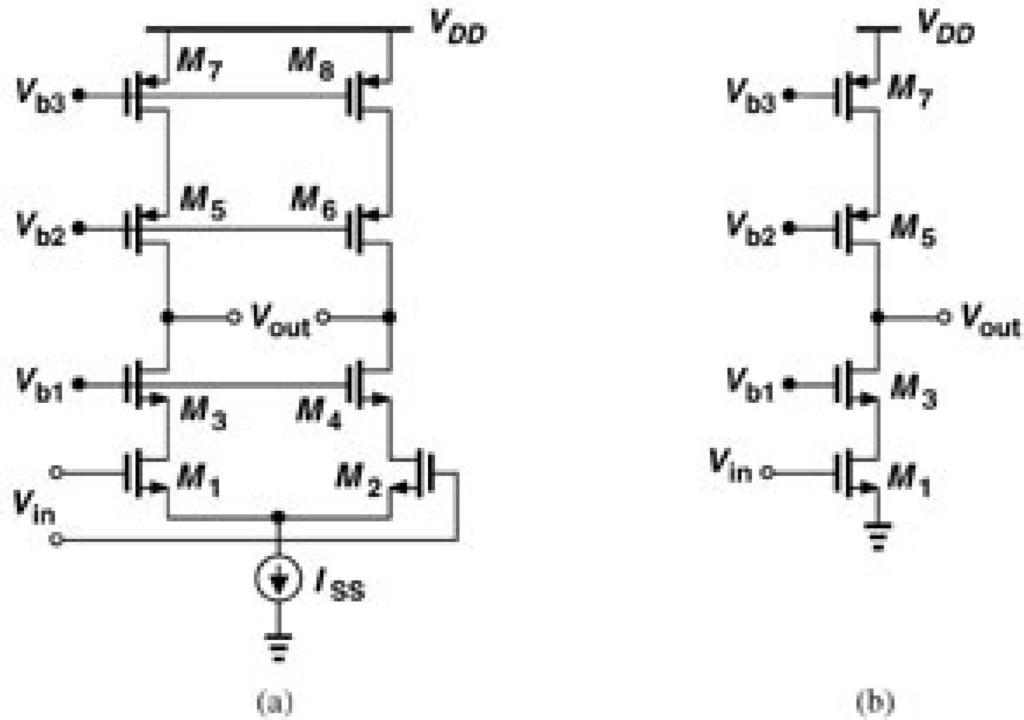
- In sub-micron technologies, it's hard to obtain differential gains higher than 10-20.

Problem: How to increase the gain for current-source MOS load?

Solution:

- From B, increase the gain by increase the output impedance.

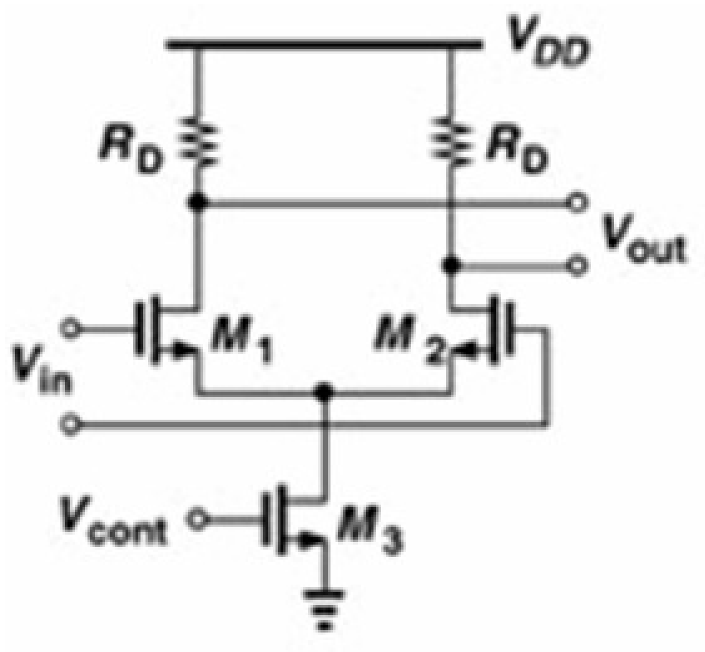
Solution to low-gain problem: Cascoding



$$A_{V,diff} \approx g_{m1}[(g_{m3}r_{o3}r_{o1}) \| (g_{m5}r_{o5}r_{o7})]$$

- We can increase the output impedance of both PMOS and NMOS devices by cascoding.
- Cascoding increases the differential gain substantially but at the cost of consuming more voltage headroom.

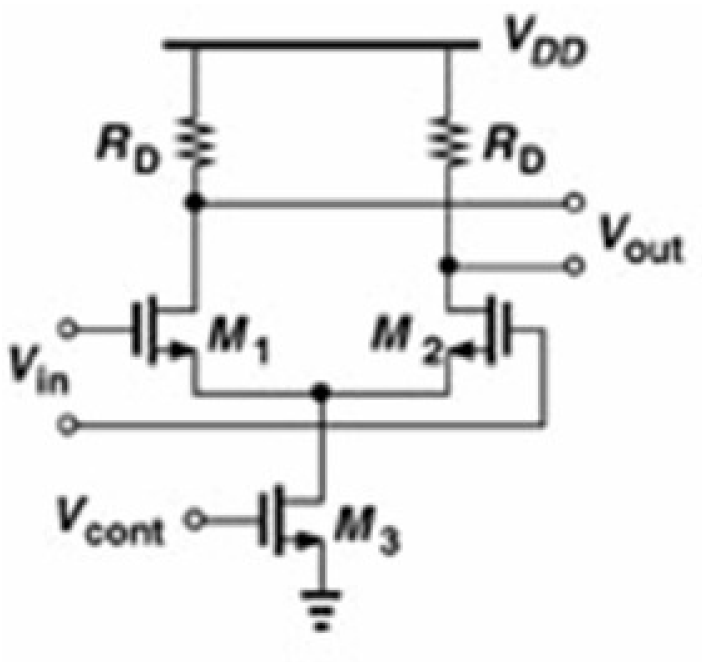
Gilbert Cell



(a)

- Our study of differential pairs reveals two important aspects of their operations:
  - The small-signal gain of the circuit is a function of the tail current
  - The two transistors in a differential pair provide a simple means of steering the tail current to one of two destination
- By combining these two properties, we can develop a versatile building block.

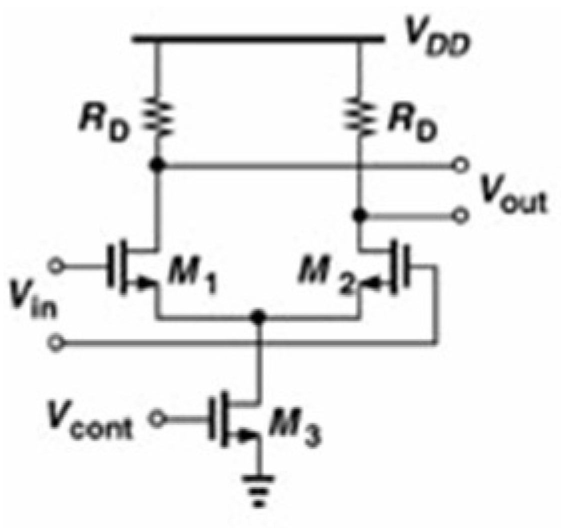
Gilbert Cell (contd …)



(a)

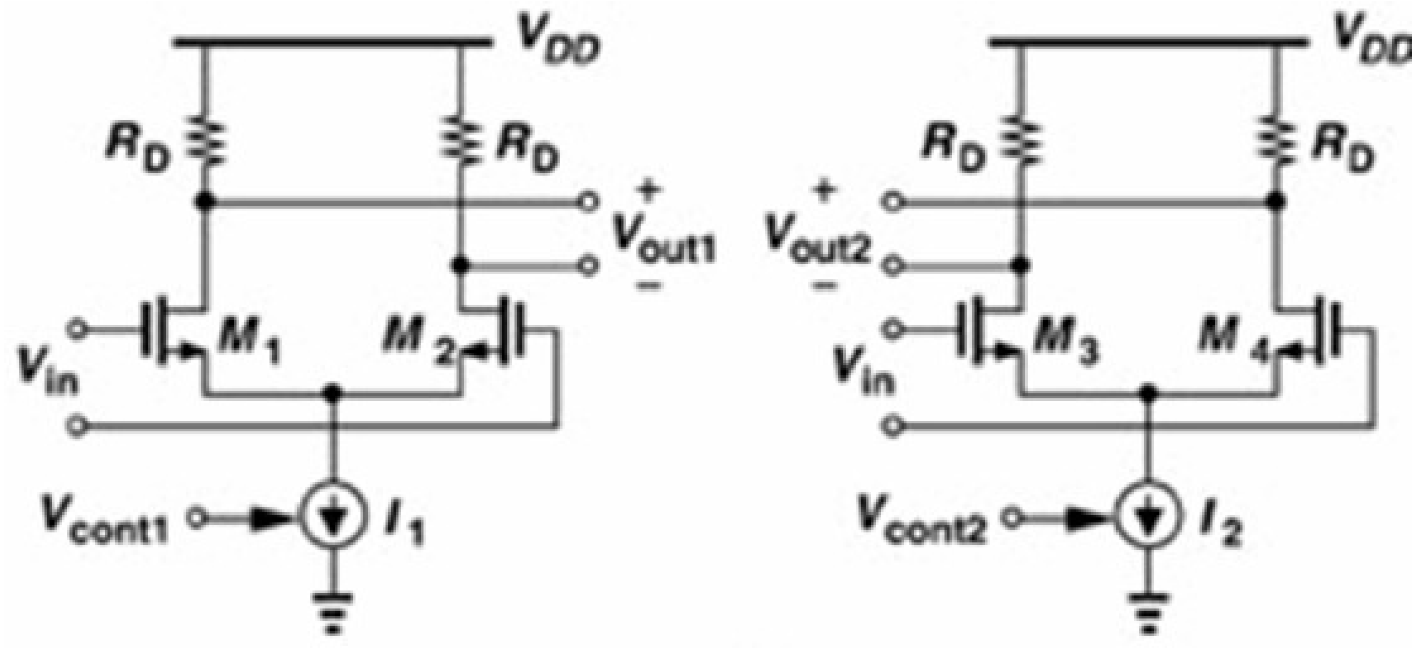
- In other word: vary Vcont → vary Iss → vary gain
- Thus we can vary the gain by vary the input voltage.
- This is useful when input signal amplitude experience large variation and hence require inverse change in gain.
- Vcont define the tail current (Iss) thus the gain.
- Max gain is given by:
  - Voltage headroom
  - Device dimension

Voltage-controlled differential gain



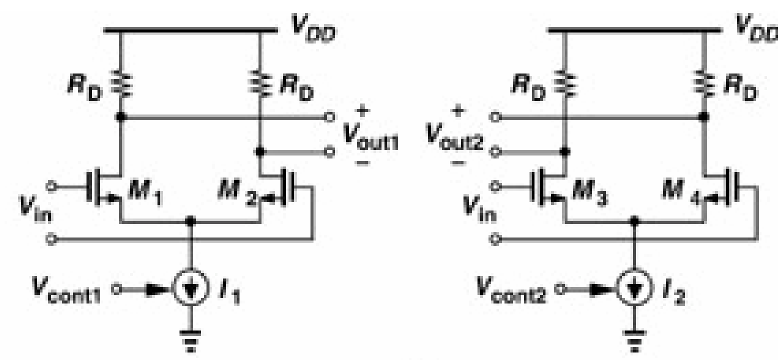
(a)

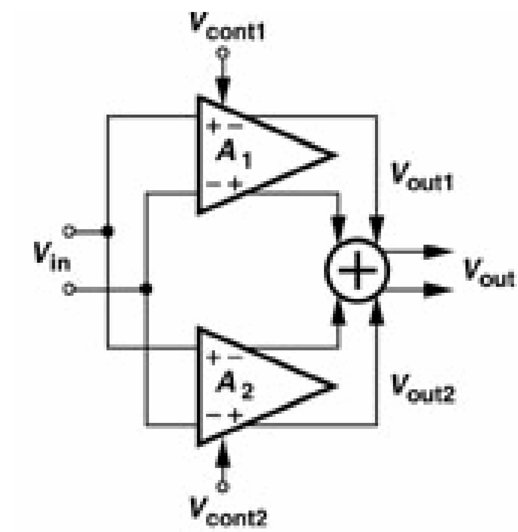
- We can create a differential pair whose gain is varied by control voltage (Fig a).
- The control voltage defines the tail current and hence the gain.
- In this topology, $A_v=V_{out}/V_{in}$ varies from zero (if $I_{D3}=0$) to a maximum value given by voltage headroom limitations and device dimensions.
- This circuit is a simple example of a “variable-gain amplifier (VGA).
- VGAs can be used in application where the signal amplitude may experience large variation and hence require inverse changes in the gain.



(b)

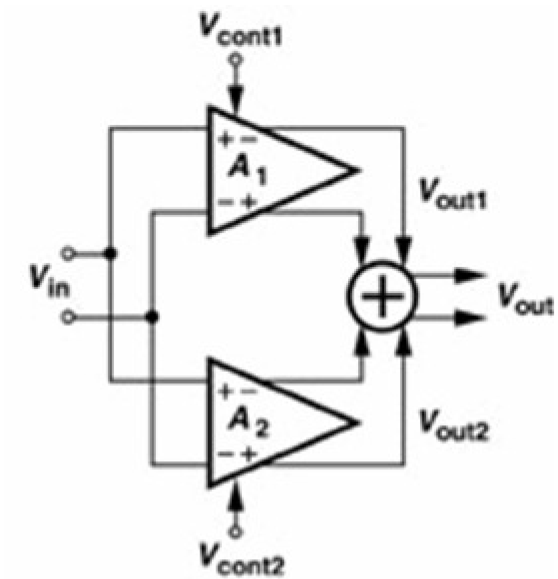
- Suppose we want an amplifier whose gain can be continuously varied from a negative value to a positive value.
- Fig (b) shows two differential pair that amplify the input by opposite gains.
- We have $V_{out1}/V_{in}=-g_mR_D$ and $V_{out2}/V_{in}=+g_mR_D$
- If I_1 and I_2 vary in opposite direction, so do $|V_{out1}/V_{in}|$ and $|V_{out2}/V_{in}|$.





(a)

- But how Vout1 and Vout2 can be combined into a single output?
- As shown in Fig (a), the two voltage can be summed, producing $V_{out}=V_{out1}+V_{out2}=A_1V_{in}+A_2V_{in}$, where A_1 and A_2 are controlled by V_{cont1} and V_{cont2}, respectively

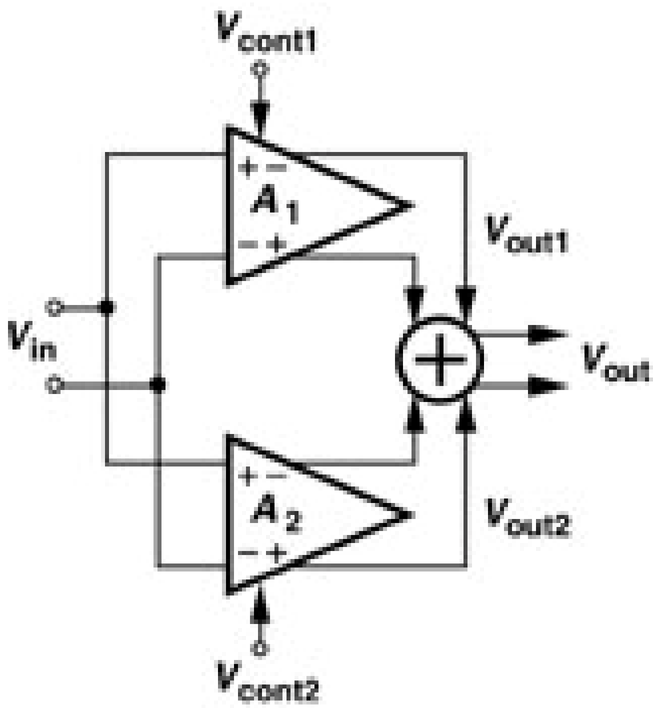


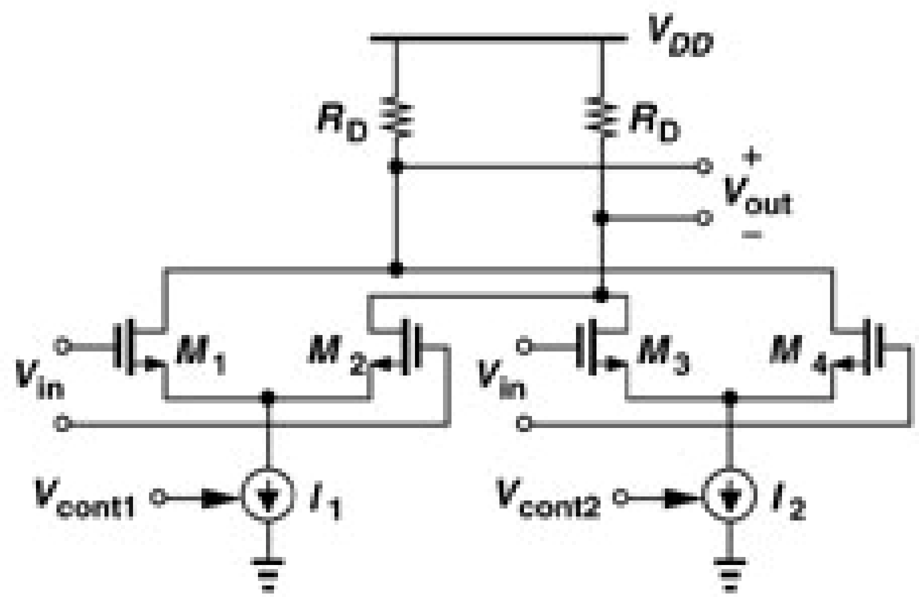
The actual implementation is quite simple: since

$V_{out1}=R_D I_{D1}-R_D I_{D2}$ and
$V_{out2}=R_D I_{D4}-R_D I_{D3}$,

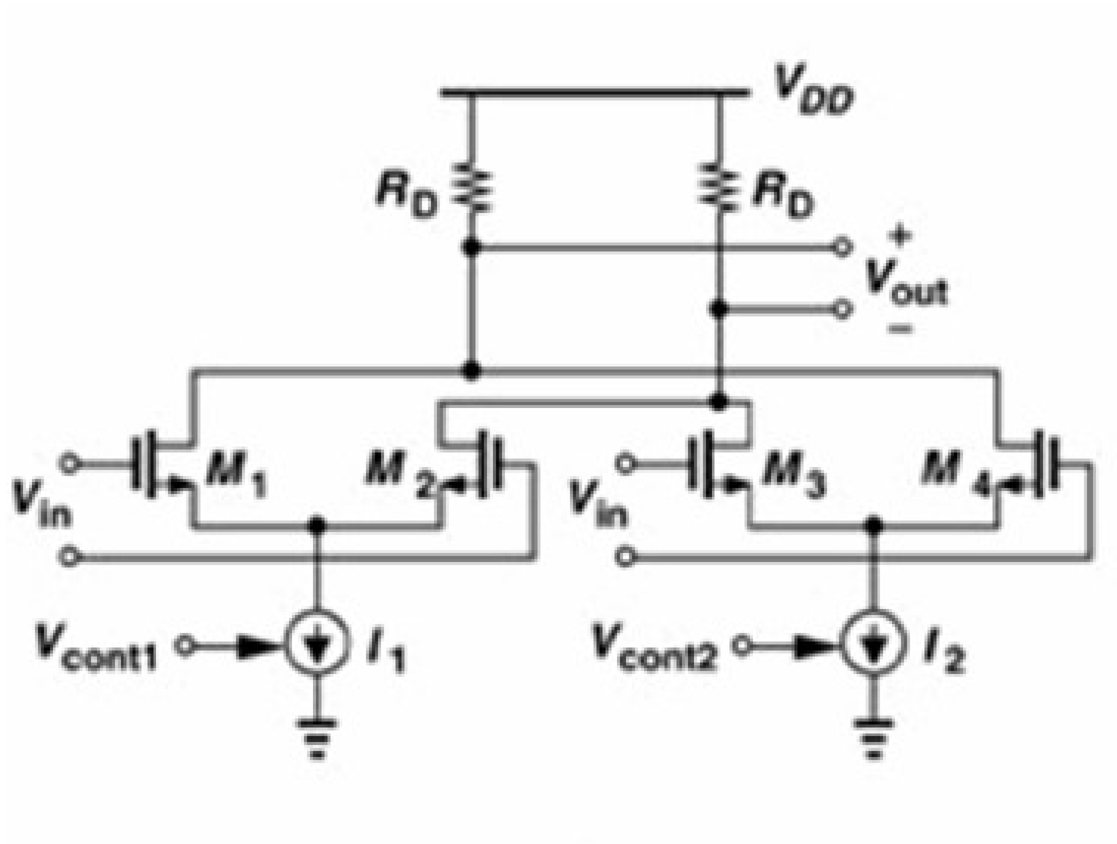
we have:

$V_{out1}+V_{out2}=R_D(I_{D1}+I_{D4})-R_D(I_{D2}+I_{D3})$



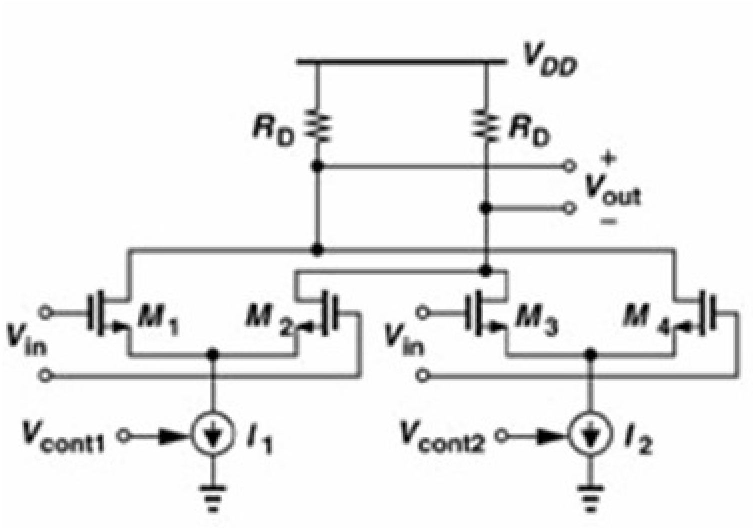


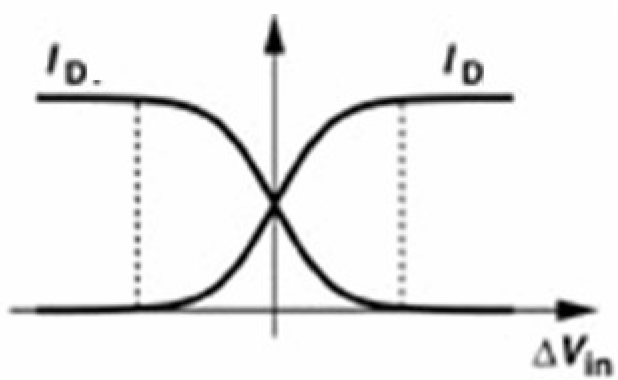
Thus, rather than add the voltage Vout1 and Vout2, we add the current by simply short the corresponding drain terminals to sum the currents (and subsequently generate the output voltage).



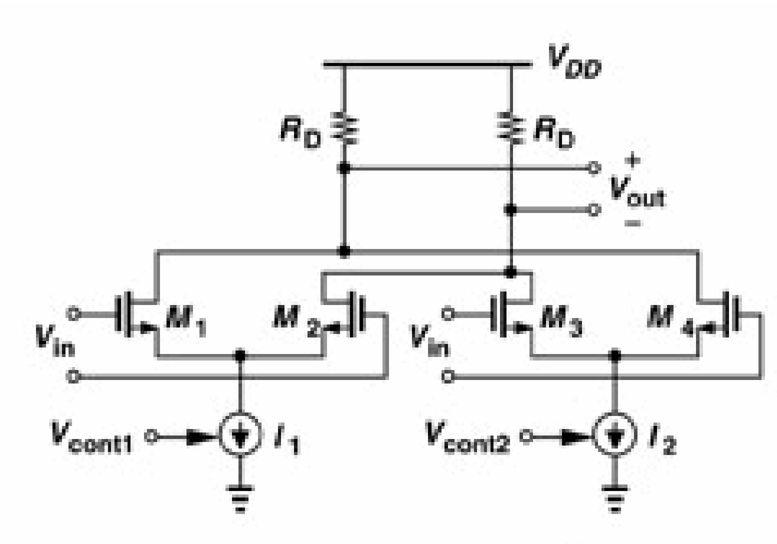
Note that:

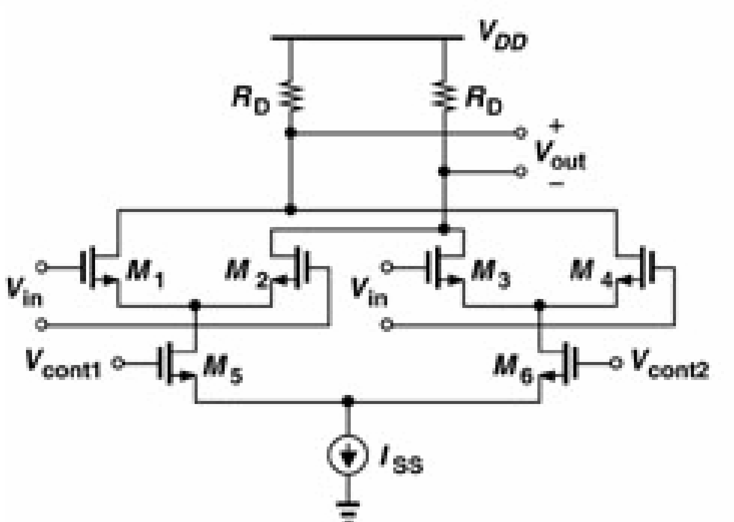
- If I_1=0, then V_{out}=+$g_m R_D V_{in}$ and
- If I_2=0, then V_{out}=-$g_m R_D V_{in}$.
- For I_1=I_2, the gain drop to zero.



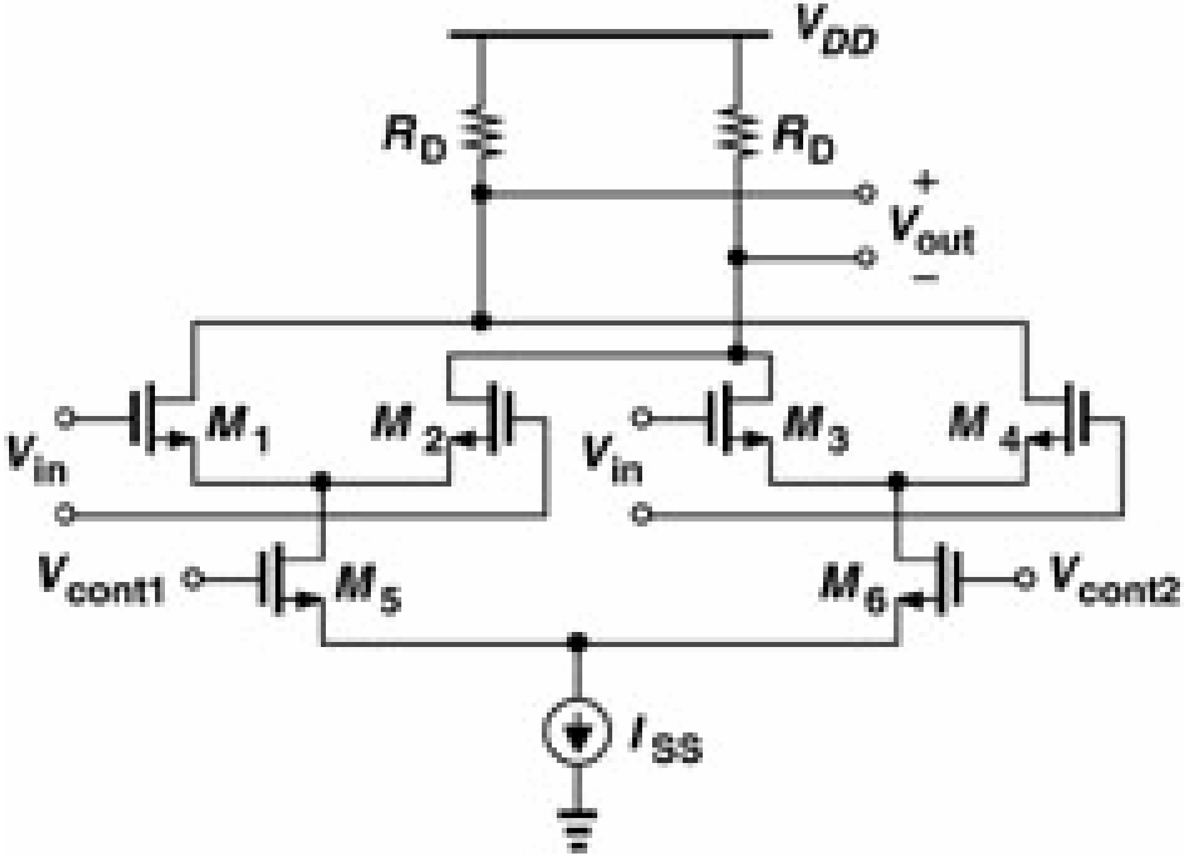


- Note that V_{cont1} and V_{cont2} must vary I_1 and I_2 in opposite directions such that the gain of the amplifier changes monotonically.
- What circuit can vary two currents in opposite direction?

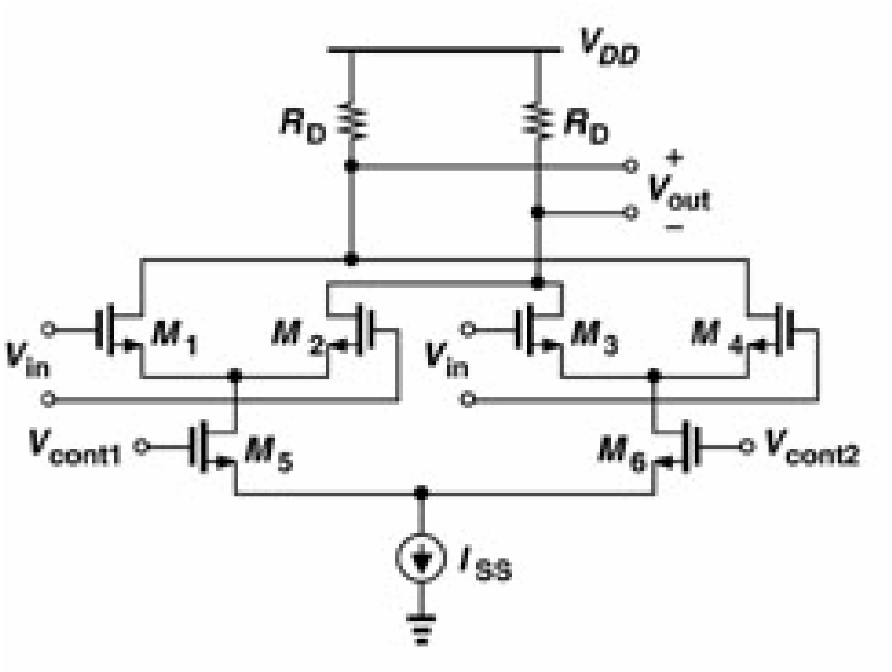




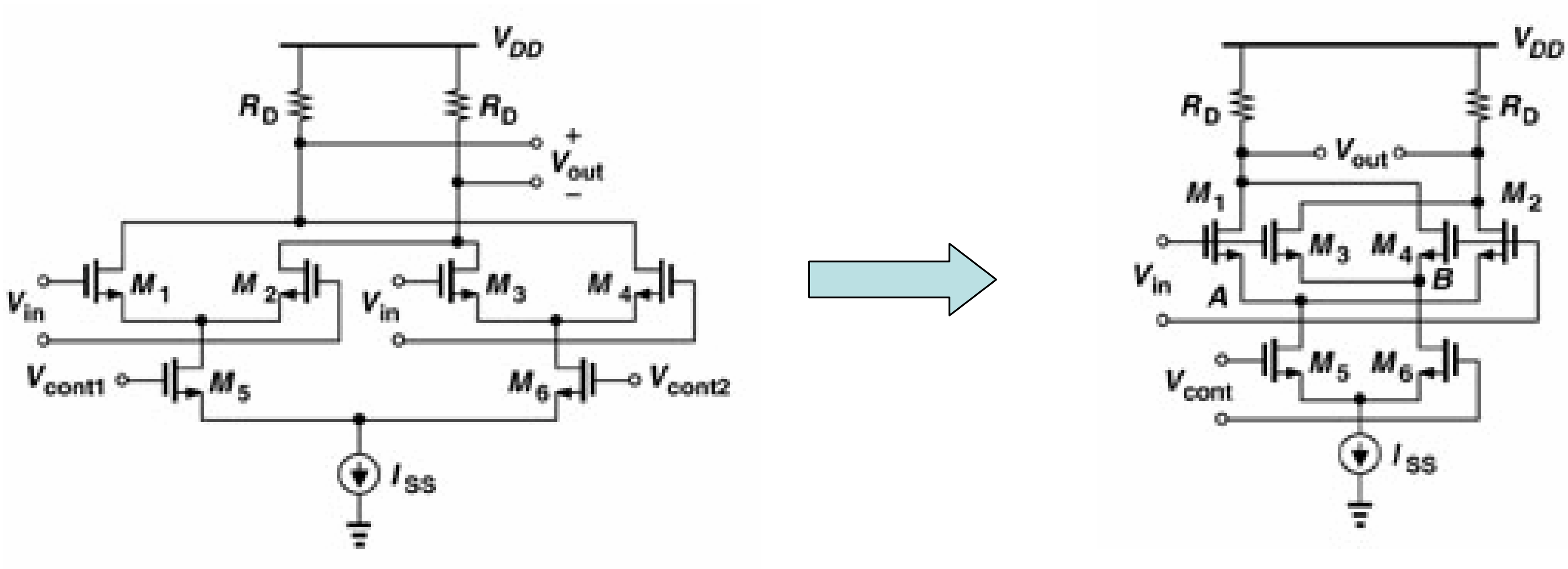
- What circuit can vary two currents in opposite direction? → A differential pair provides such a characteristic, leading to the topology shown in the figure



V_{DD}
R_D
R_D
+
V_{out}
−
M_1
M_2
M_3
M_4
V_{in}
V_{in}
V_{cont1}
M_5
M_6
V_{cont2}
I_{SS}



- Note that for a large $|V_{cont1}-V_{cont2}|$, all of the tail current is steered to one of the top differential pairs and the gain from Vin to Vout is at its most positive or most negative values.
- For $|V_{cont1}=V_{cont2}|$, the gain is zero.



- For simplicity, the circuit is redraw.
- This circuit is called “Gilbert Cell”, this circuit is widely used in many analog and communication systems.
- In typical design, M1-M4 are identical and so M5 and M6.