Advanced Analog Building Blocks
Differential amplifiers

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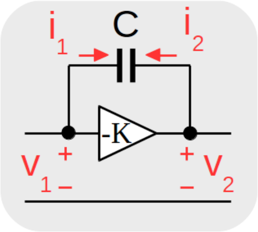
Course web

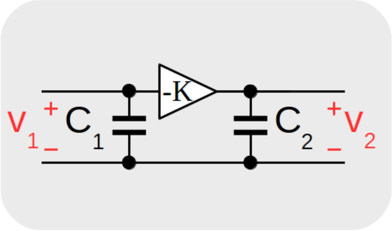
SoSe 2017

- **Next lectures after holidays:**
  - 25.5 $\rightarrow$ lecture Friday 26^{th}
  - 15.6 $\rightarrow$ lecture Friday 16^{th}

- Should we proceed as normal days (attendance)?
- Run some more cadence lab on one of those days?

Introduction: Miller Effect





$$i_1 = \frac{v_1 - v_2}{Z} = \frac{v_1 + K v_1}{Z} = \frac{1+K}{Z} v_1$$

$$\frac{v_1}{i_1} = \frac{Z}{1+K} = \frac{1}{(1+K)Cs}$$

$$i_2 = \frac{v_2 - v_1}{Z} = \frac{v_2 + \frac{v_2}{K}}{Z} = \frac{1+\frac{1}{K}}{Z} v_2$$

$$\frac{v_2}{i_2} = \frac{Z}{1+\frac{1}{K}} = \frac{1}{\left(1+\frac{1}{K}\right)Cs}$$

$$C_1 = (1+K)\,C$$

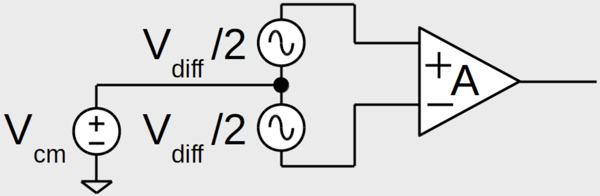
$$C_2 = \left(1+\frac{1}{K}\right)C$$

for $K >> 1 \rightarrow C_1 >> C \quad , \quad C_2 \approx C$

Caution!

Miller effect is usually calculated for $K(w)$ at medium frequencies. Extrapolation to high frecuencies produces error.

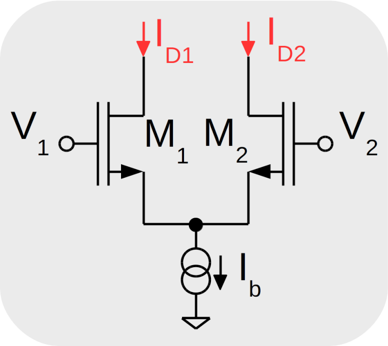
Introduction: Differential amplifier key elements



- Two terminals input (differential).
- Flexibility in configuration / feedback options (OPamp).
- **Commmon mode**: DC voltage present at both inputs.
- **Differential input**: small signal present at input: $V_+ - V_-$
- **Common Mode Rejection Ratio, CMRR**: immunity to changes in common mode.
- **Power Supply Rejection Ratio, PSRR**: immunity to changes in power supply.

The Differential Pair: circuit basics

- Usually a difference of voltages need to be amplified.



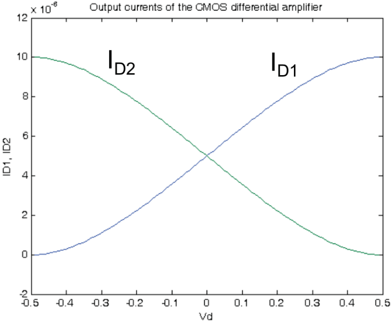
Differential voltage:

$$V_d = V_1 - V_2$$

Common-mode:

$$V_c = \frac{V_1 - V_2}{2}$$

$$V_1 = V_c + \frac{V_d}{2} \quad , \quad V_2 = V_c - \frac{V_d}{2}$$



Assuming both in saturation:

$V_1 = V_2 \rightarrow I_{D1} = I_{D2} = \frac{I_b}{2}$

$V_1 \gg V_2 \rightarrow I_{D1} \approx I_b \rightarrow I_{D2} \approx 0$

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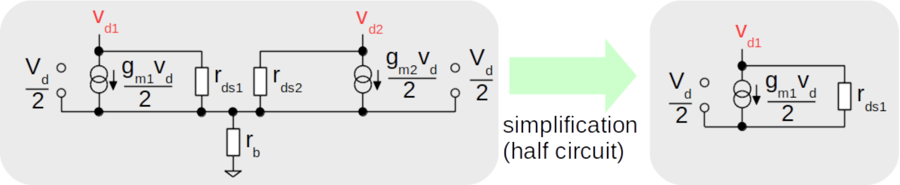
The Differential Pair: small signal analysis

- Intrinsic gain in differential mode.



$$Av_1 = \frac{v_{d1}}{v_d} = \frac{-g_{m1} r_{ds1}}{2}$$

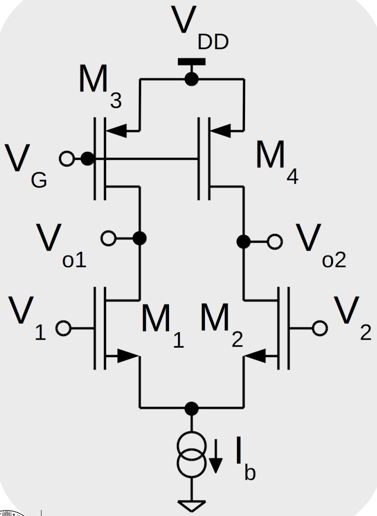
Transconductance amplifier (voltage to current conversion);

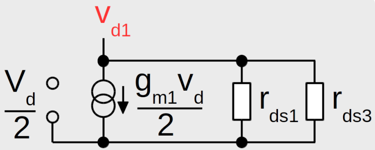
$$g_1 = \frac{i_{d1}}{v_d} = \frac{g_{m1}}{2}$$

Caution!

Devices must be kept in saturation.

Amplifier configurations: active load





$$Av_1 = \frac{v_{o1}}{v_d} = \frac{-g_{m1}(r_{ds1}//r_{ds3})}{2} = \frac{-g_{m1}}{2(g_{o1}+g_{o3})}$$

Assuming $M_1 = M_2, M_3 = M_4$ then $g_{m1} = g_{m2}, g_{o1} = g_{o2}, g_{o3} = g_{o4}$ the differential gain is;

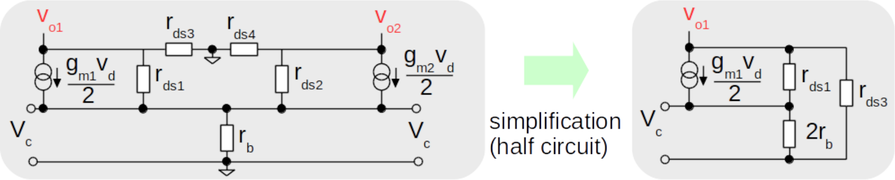
$$Av_d = \frac{v_{o2}-v_{o1}}{v_d} = \frac{-g_{m1}}{g_{o1}+g_{o3}}$$

Caution!

V_G must guarantee that $I_{D3} + I_{D4} = I_b$

Amplifier configurations: common mode gain

- Intrinsic gain in differential mode.



Neglecting the current flow in r_{ds1};

$$Av_{c1} = \frac{v_{o1}}{v_c} \approx \frac{-g_{m1}r_{ds3}}{1+2g_{m1}r_b}$$

Amplifier configurations: CMRR

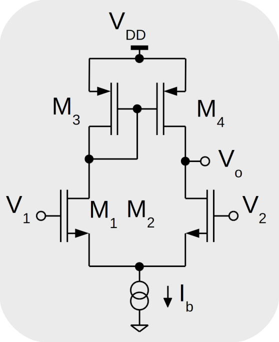
$$CMRR = \left|\frac{Av_d}{Av_{c1}}\right| = \frac{-g_{o3}(1+2g_{m1}rb)}{2(g_{o1}g_{o3}}$$

$$\text{If } g_{o1} = g_{o3}, CMRR \approx \frac{g_{m1}r_b}{2}$$

CMRR

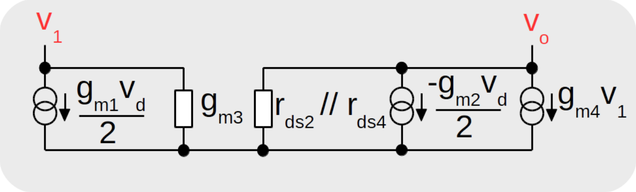
Increasing the differential pair transconductance or r_b, the CMRR raises!.

Amplifier configurations: assymetric

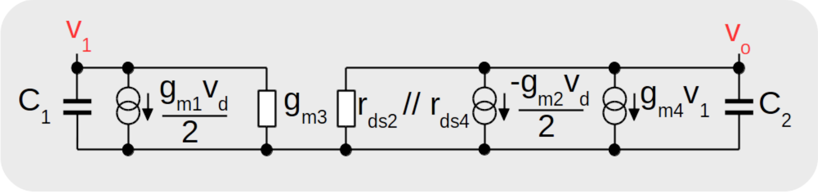


- Current mirror ensures currents are the same and half I_b

$$Av_d \approx \frac{g_{m1}}{g_{o2}+g_{o4}}$$



Amplifier configurations: assymetric frequency response



$$C_1 = C_{GD1} + C_{BD1} + C_{GS3} + C_{GS4} + C_{BD3}$$
$$C_2 = C_{GD2} + C_{BD2} + C_{GD4} + C_{BD4} + C_L$$
$$R_1 = \frac{1}{g_{m3}}, R_2 = \frac{1}{g_{o2}+g_{o4}}$$

Then (with $g_{m1} \approx g_{m2}$):

$$A_v \approx \frac{g_{m1}}{2}\frac{R_2\omega_2}{s+\omega_2}\left(1 + \frac{g_{m4}R_1\omega_1}{s+\omega_1}\right) \text{ where } \omega_1 = \frac{1}{R_1C_1}, \omega_2 = \frac{1}{R_2C_2}$$

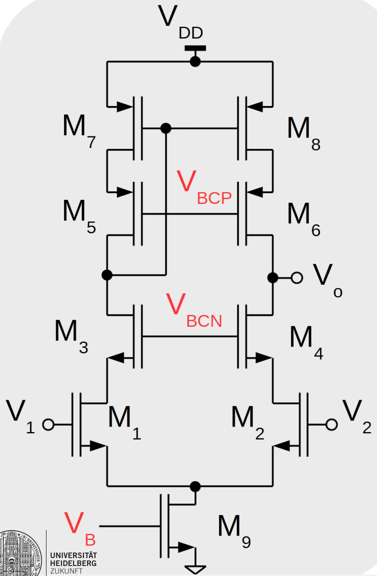
$$A_v = A_v(0)\frac{\left(\frac{s}{\omega_1'}+1\right)}{\left(\frac{s}{\omega_1}+1\right)\left(\frac{s}{\omega_2}+1\right)}$$

$$A_v(0) = \frac{g_{m1}R_2}{2}(1 + g_{m4}R_1) \approx \frac{g_{m1}}{g_{o2}+g_{o4}}, \omega_1' = \omega_1(1 + g_{m4}R_1) \approx 2\omega_1$$

A pole-zero pair is obtained, with the zero at double frequency of the pole.

The **dominant pole** is: $\omega_2 = \frac{g_{o2}+g_{o4}}{C_2}$

Telescopic cascode amplifier

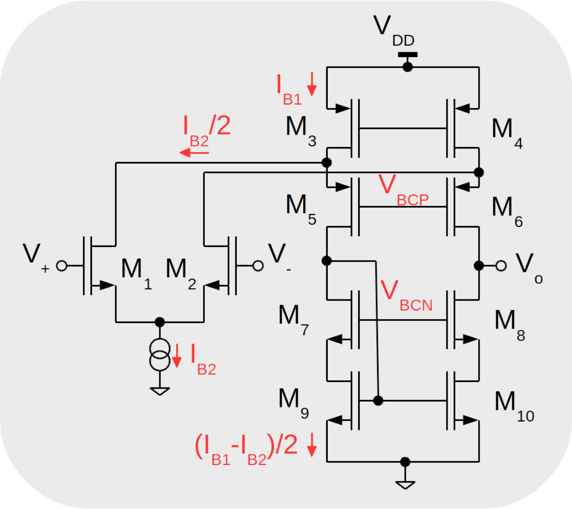


V_B, V_{BCN}, V_{BCP} are DC bias voltages generated externally to set stauration opperation point.

- Gain: $A_d = \frac{(g_m r_{ds})^2}{2}$
- Cuttoff frequency: $\omega_t = \frac{g_{m1}}{C_L}$ (other poles also)
- Output swing: $V_{DD} - 5V_{eff}$ $(V_{eff} = V_{GS} - V_{TH})$

Low Gain, Low output swing but fast and low power.

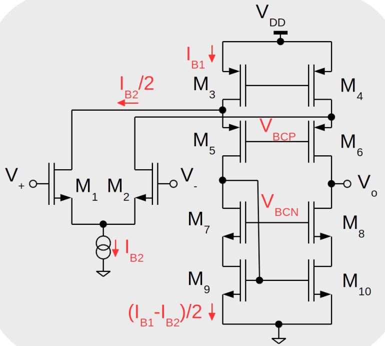
Folded cascode N input



- Slower
- Wider output swing

Folded cascode N input

- Gain: $A_d = \frac{(g_m r_{ds})^2}{2}$
- Cuttoff frequency: $\omega_t = \frac{g_{m1}}{C_L}$ (other poles also)
- Output swing $V_{DD} - 4V_{eff}$
- Wider output swing



Folded cascode P input