Differential
Voltage & Current amplifiers

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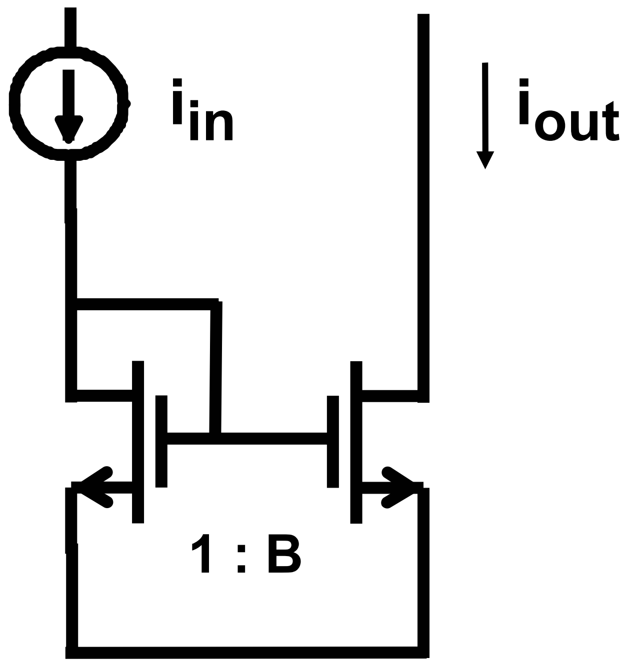
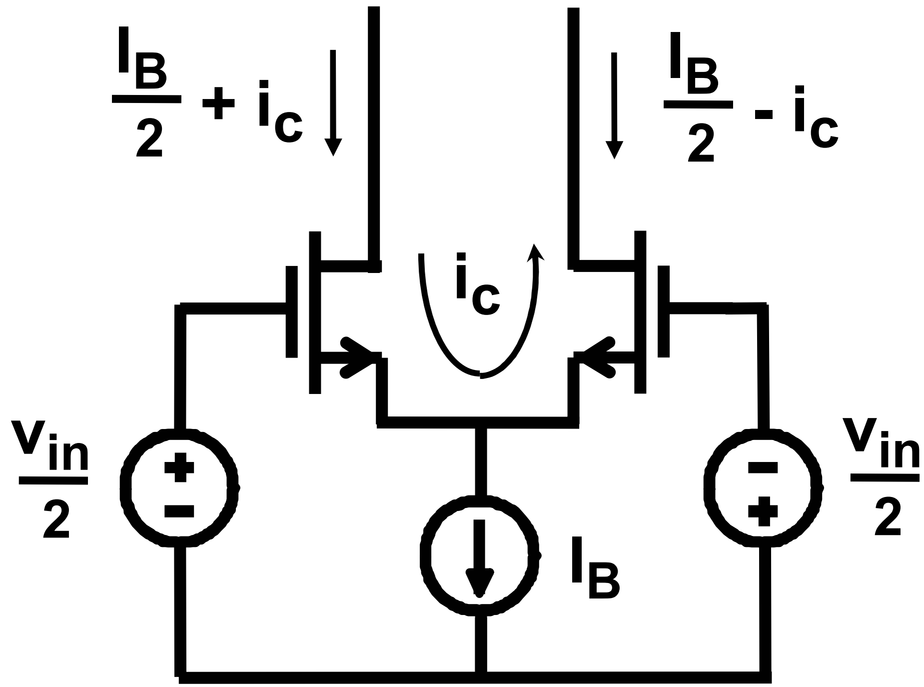
Two-transistor circuits



$$i_{out} = B\ i_{in}$$

Current mirror/amp.



$$i_c = g_m \frac{v_{in}}{2}$$

Differential Voltage amp.

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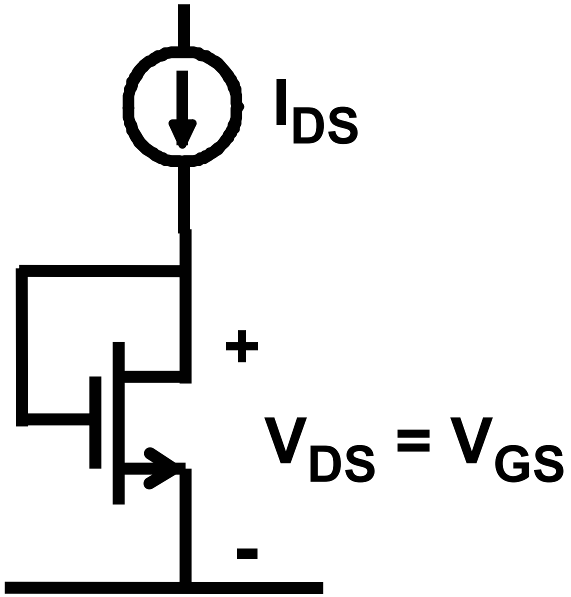
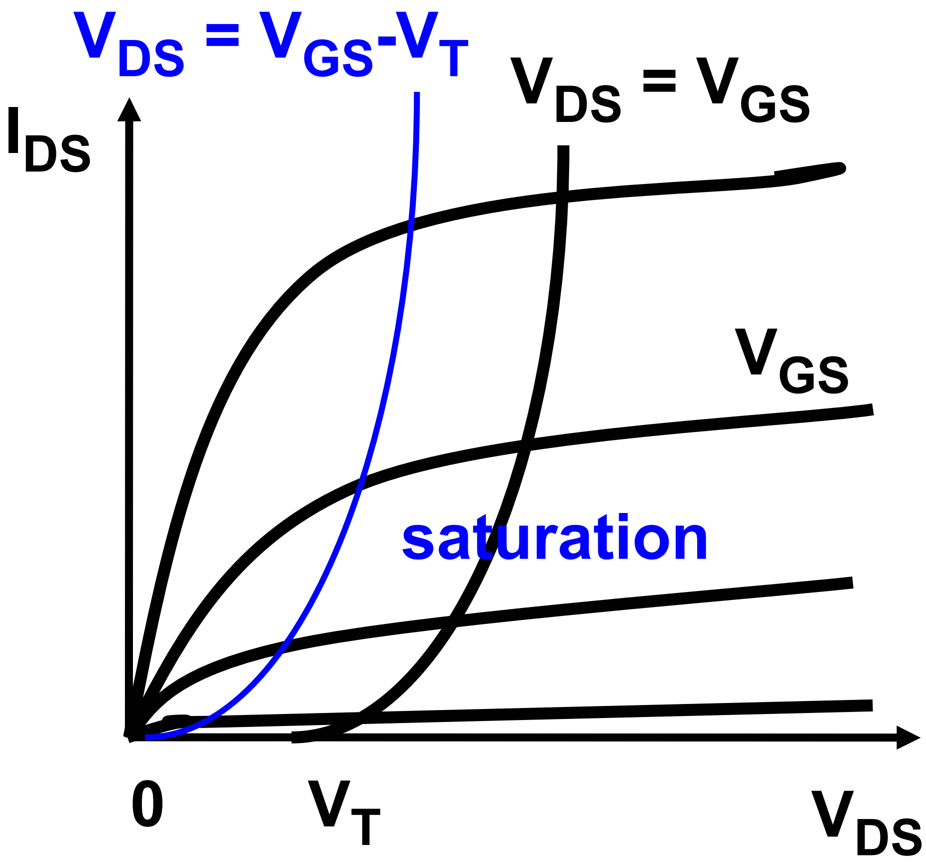
Diode-connected MOST



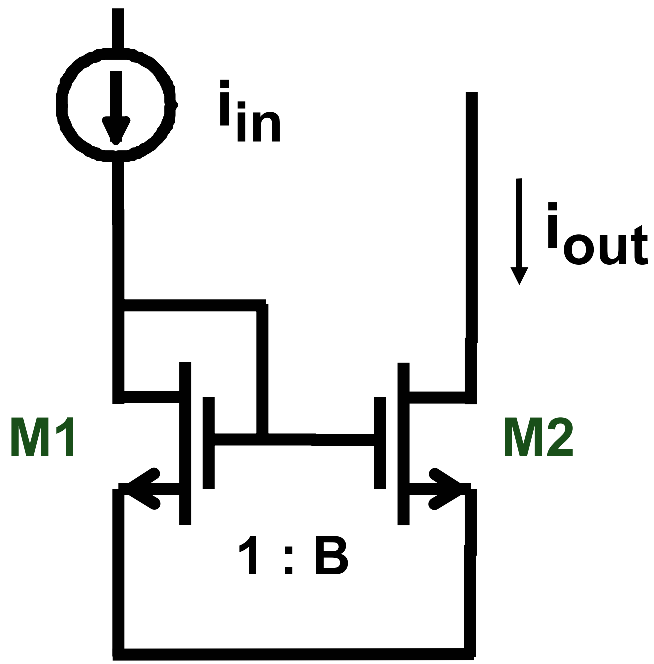
G = D

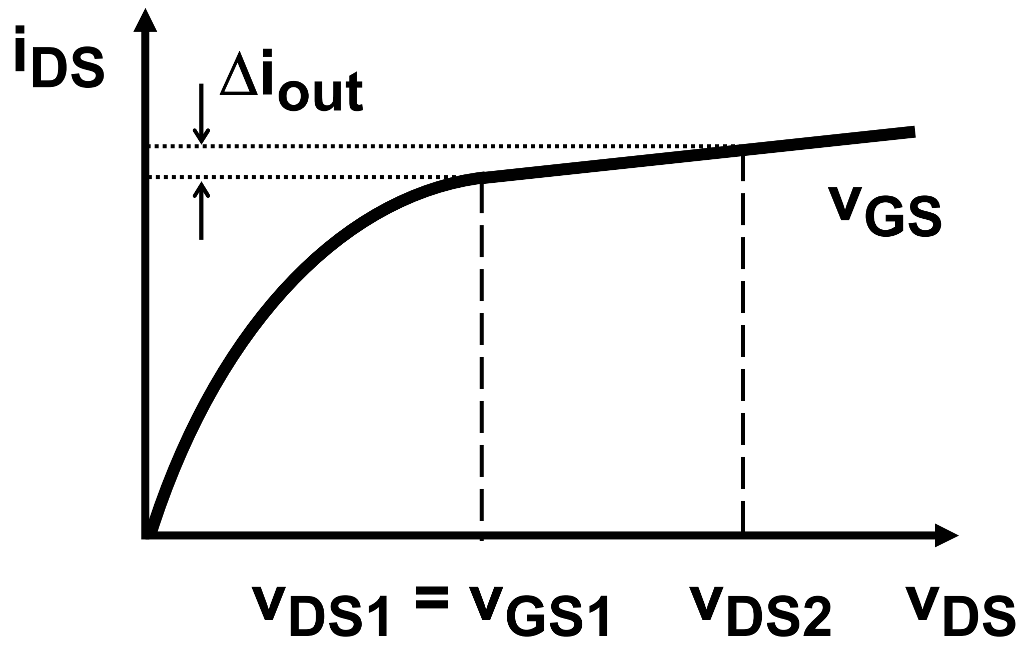


$$I_{DS} = K'_n \frac{W}{L} (V_{DS}-V_T)^2$$

$$g_m = di_{DS} / dv_{DS}$$

Current mirror

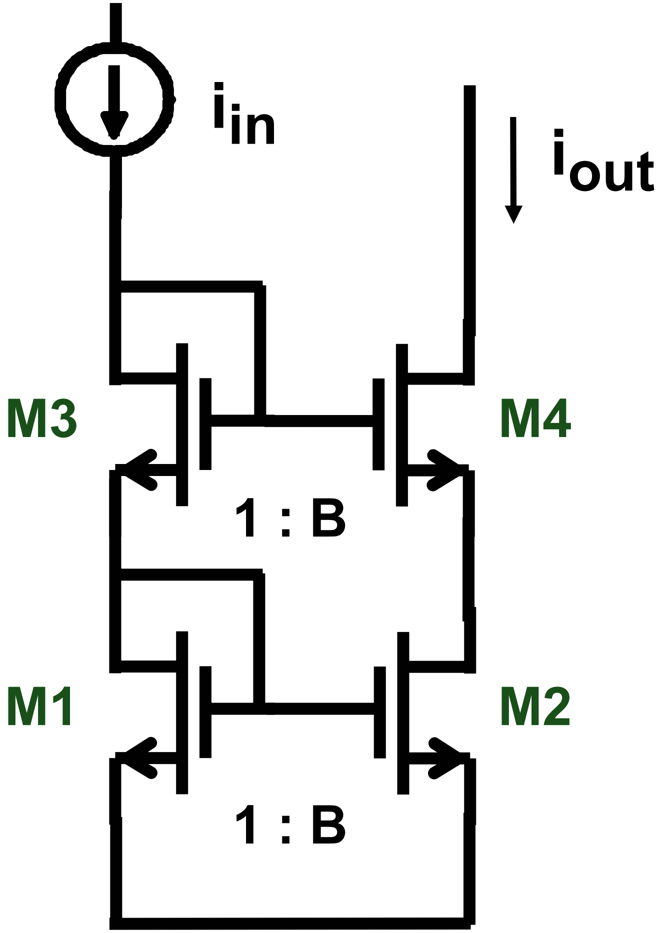


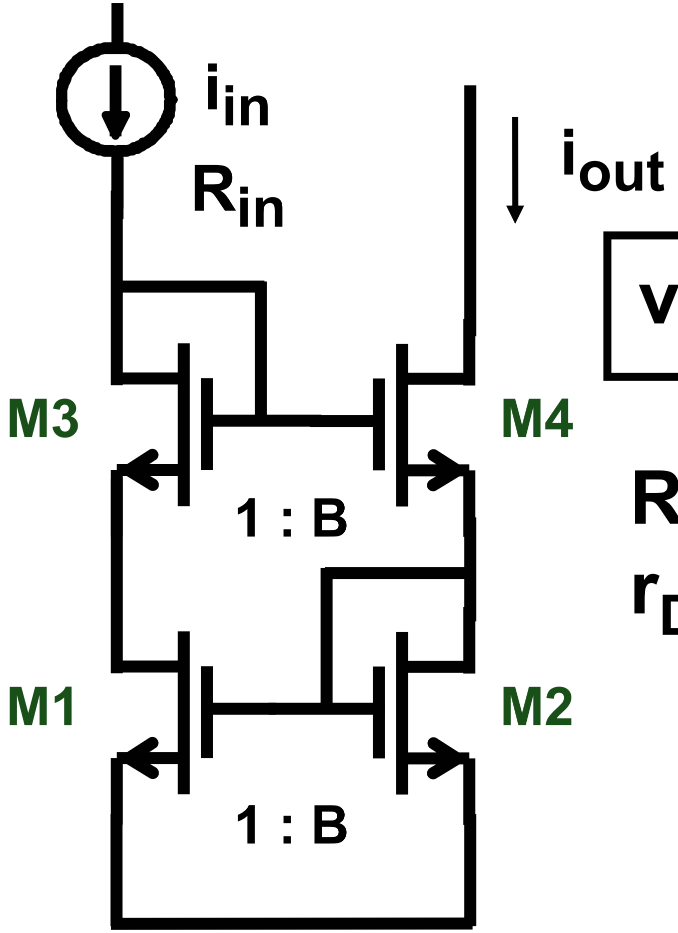


$$i_{out} = B\ i_{in}$$

$$\frac{\Delta i_{out}}{i_{out}} = \frac{v_{DS2} - v_{DS1}}{V_E L_2}$$

Improved current mirrors





Feedback $T \approx g_{m1}R_{in}$

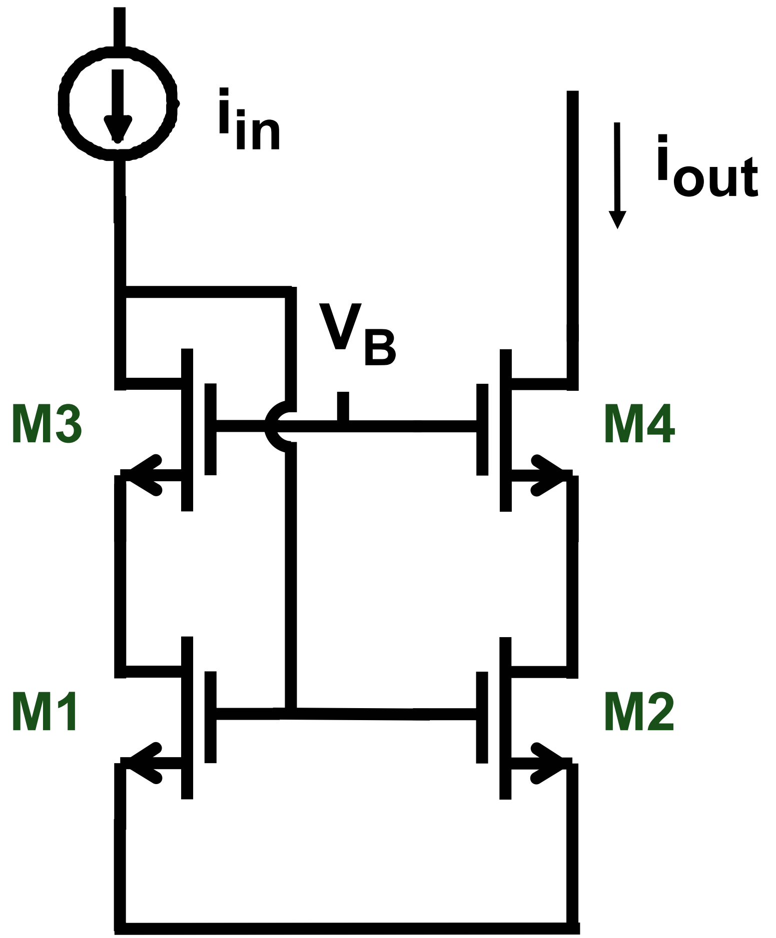
$v_{DS2} = v_{DS1}$

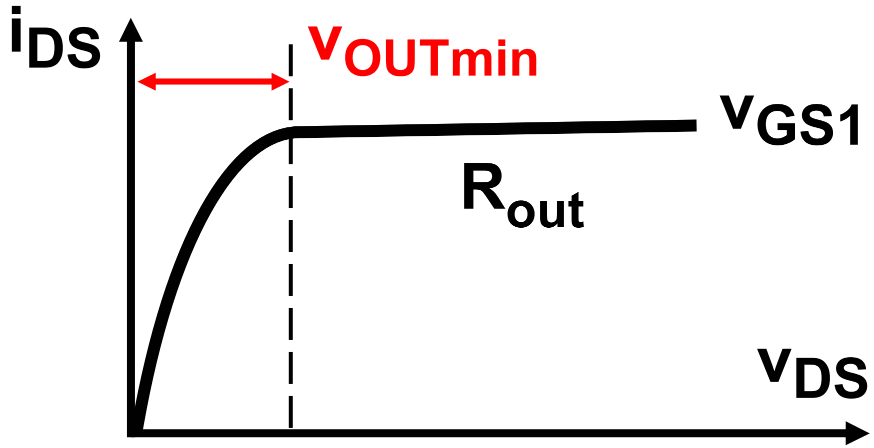
$R_{out} = r_{DS2}\, g_{m4} r_{DS4}$

$v_{OUTmin} = v_{GS} + v_{DS} \approx 0.9+0.2=1.1$ V

Is too large !!!

Low-voltage current mirror





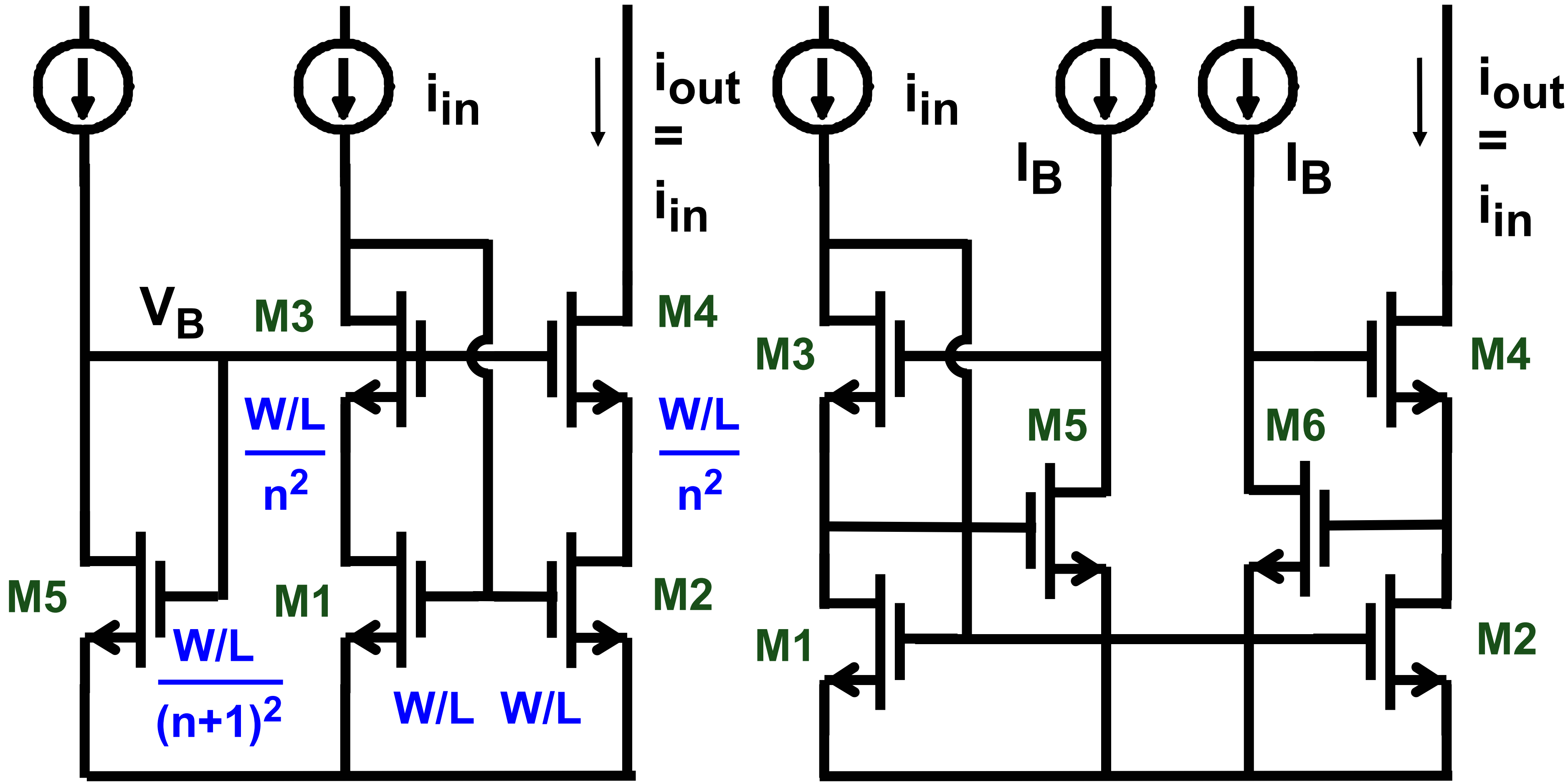
$$v_{DS2} = v_{DS1}$$

$$R_{out} = r_{DS2}\, g_{m4} r_{DS4}$$

$$v_{OUTmin} = v_{DS2} + v_{DS4}$$

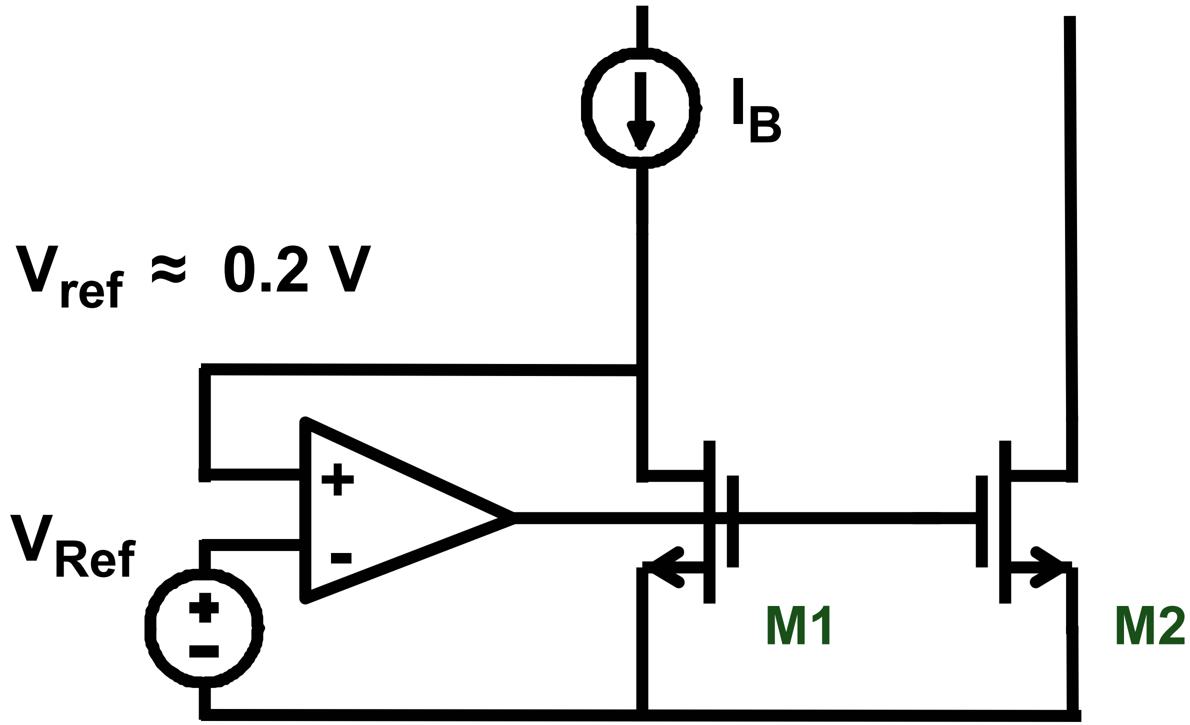
$\approx 0.2 + 0.2 = 0.4$ V is low !

Examples of low-voltage current mirrors



Low-voltage diode-connected MOST

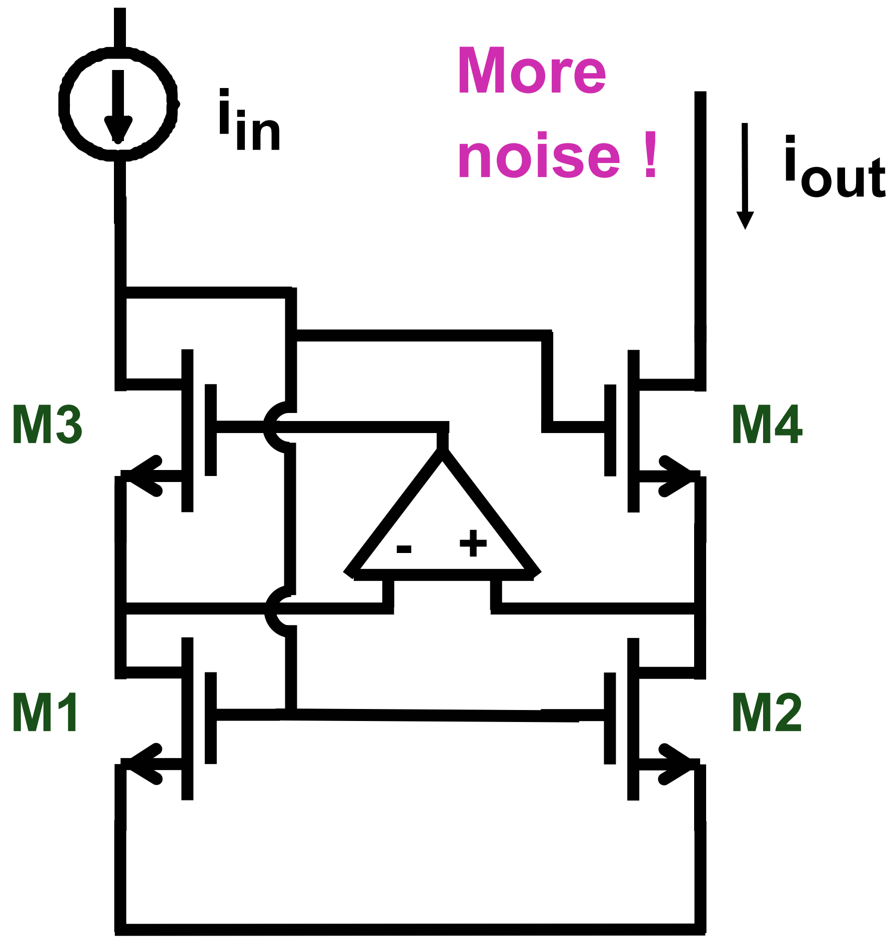
$V_{ref} \approx 0.2\ V$

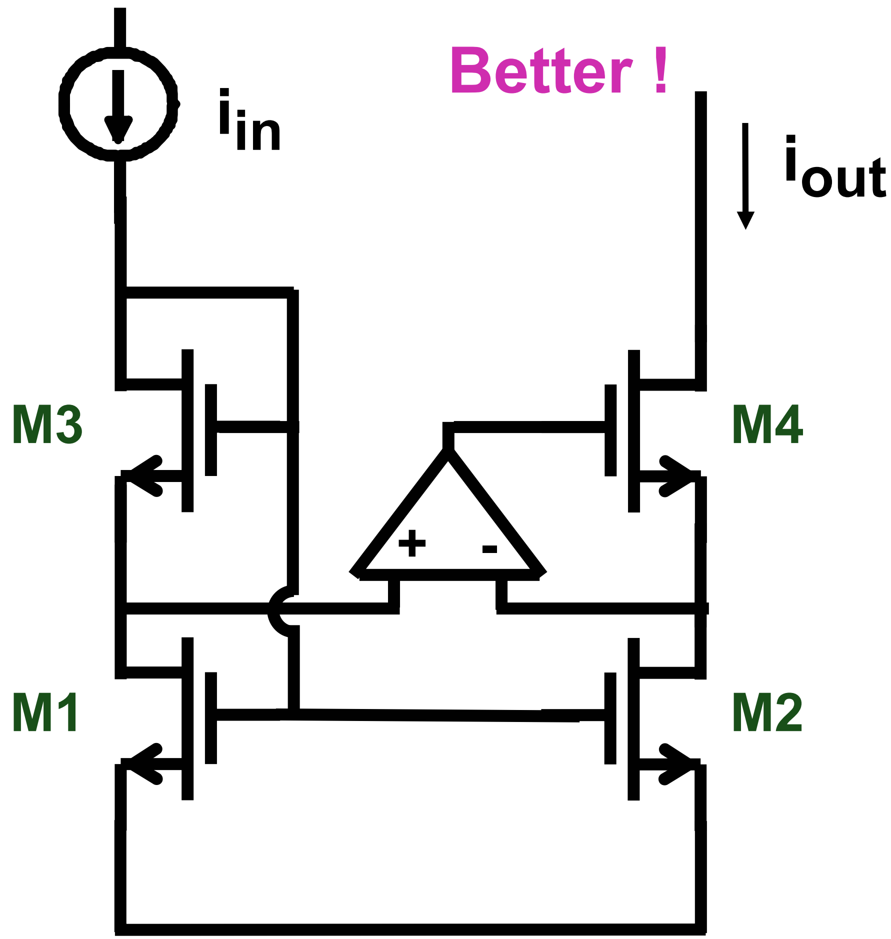


$V_{DSmin} \approx 0.2\ V$

$R_{out} = r_{DS2}$

Lowest-voltage current mirrors

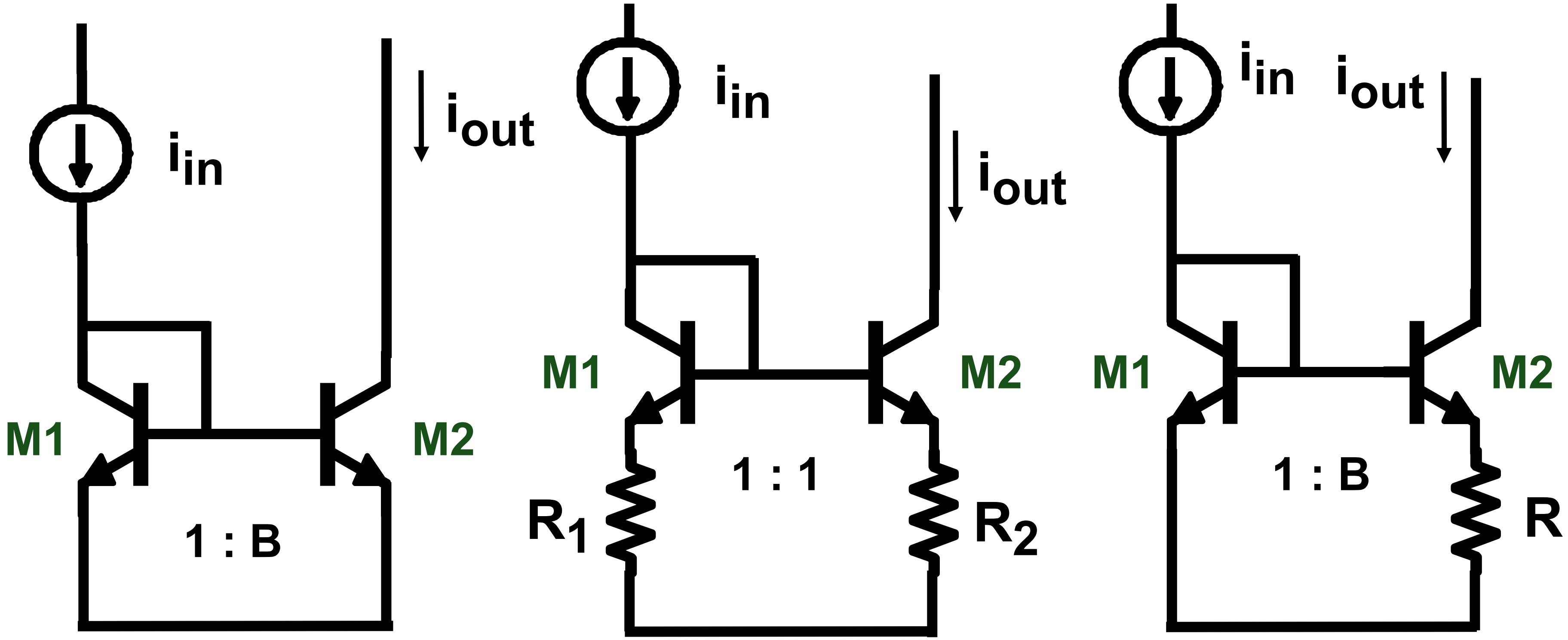




$v_{OUTmin} \approx 50$ mV

Ref.: Charlon, .., ESSCIRC 2004

Current mirror



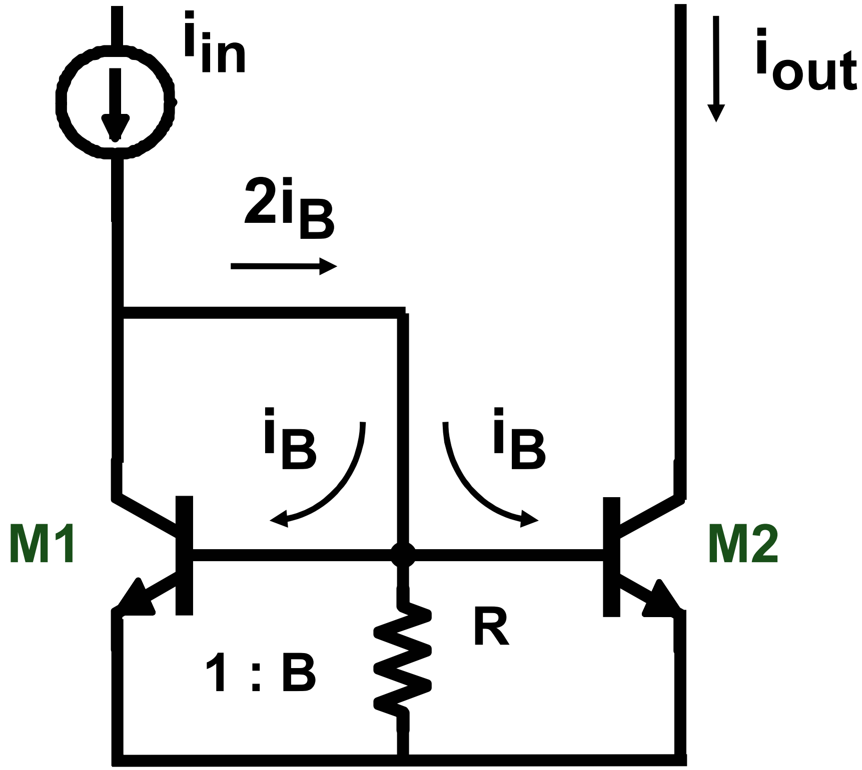
$i_{out} = B\ i_{in}$

$$\frac{i_{out}}{i_{in}} = \frac{R_1}{R_2}$$

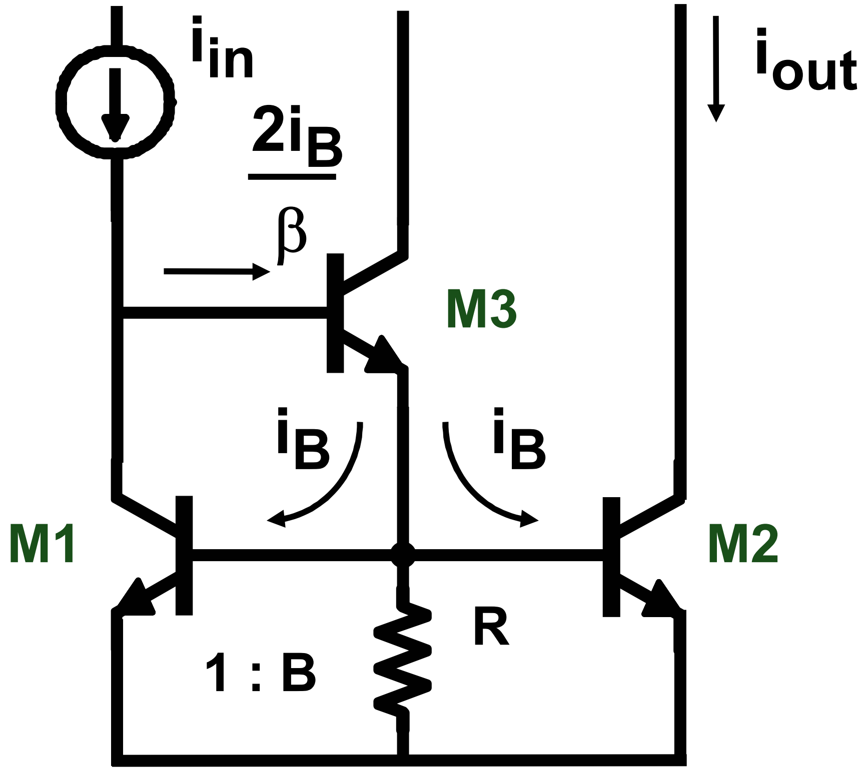
$$i_{out} = \frac{kT/q}{R} \ln B \frac{i_{in}}{i_{out}}$$

Ref.: Widlar, JSSC Aug 69, 184-191

Improved current mirrors

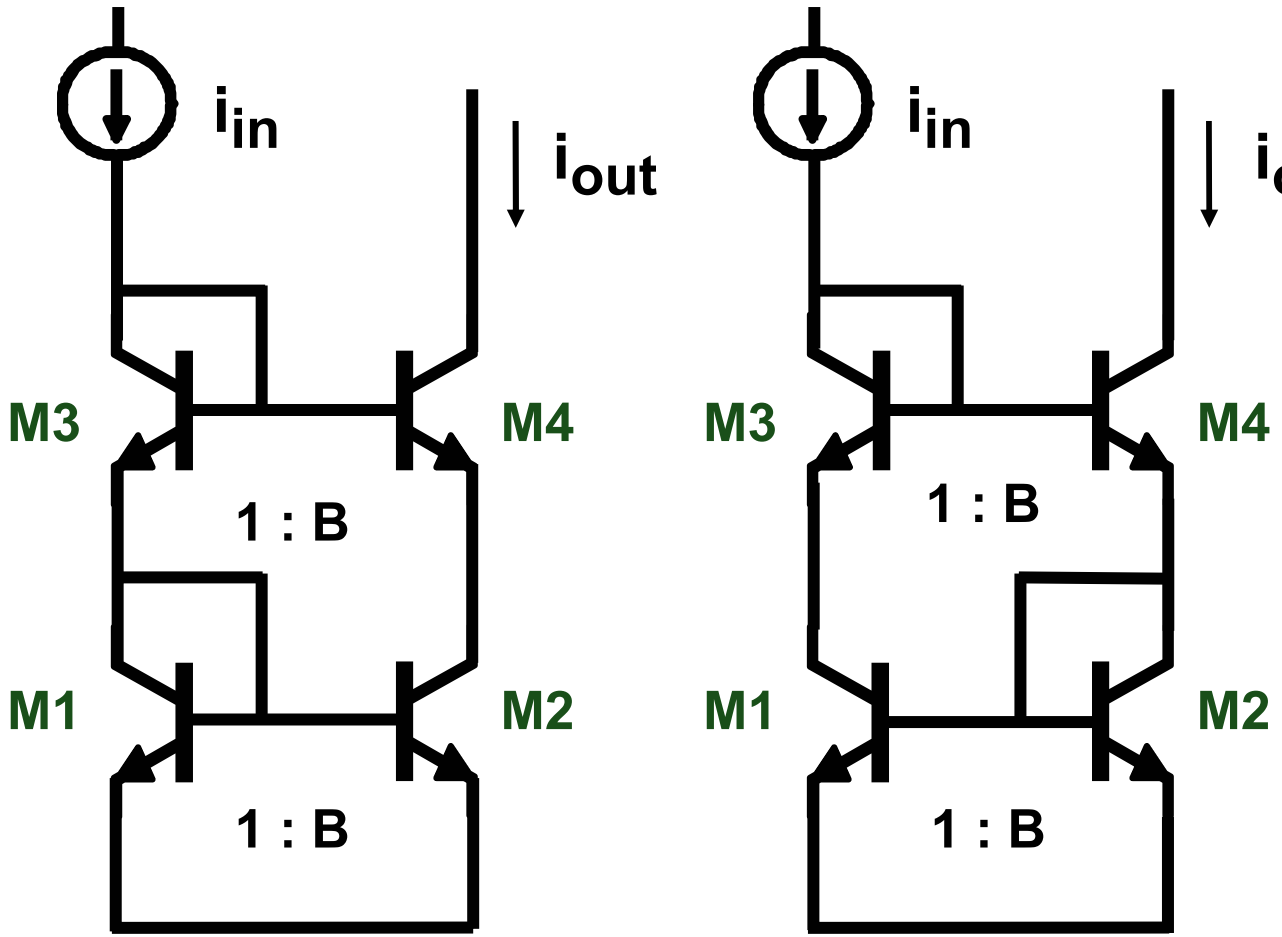


$$\text{Error} \sim \frac{2}{\beta}$$



$$\text{Error} \sim \frac{2}{\beta^2}$$

Improved current mirrors



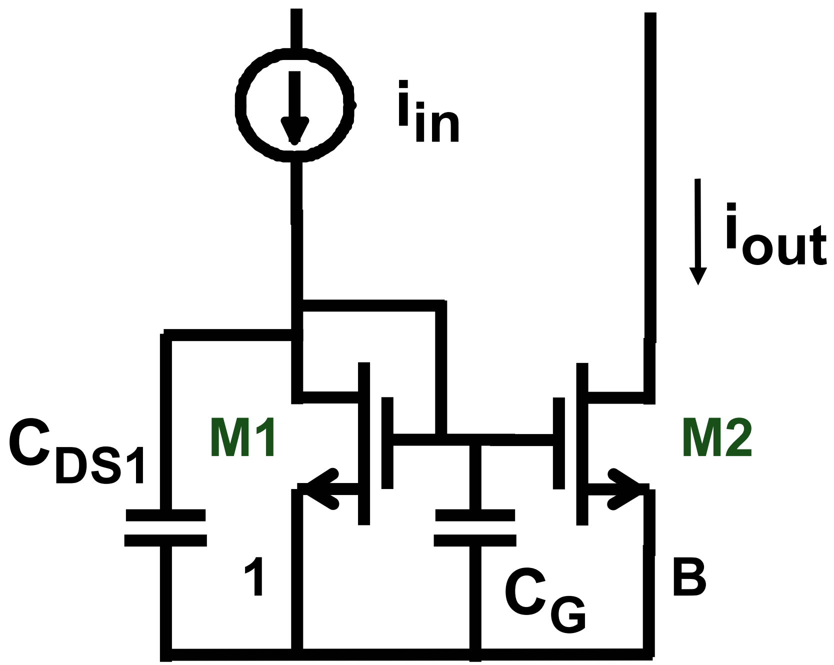
$v_{CE2} = v_{CE1}$

R_{out} =
$r_{o2}\, g_{m4} r_{o4}$

v_{OUTmin}
$= v_{BE} + v_{CE}$
$\approx 0.7+0.1 = 0.8$ V
Is too large !

Ref.: Wilson, JSSC Dec.68, 341-348

Current mirror at high frequencies



$$i_{out} = B\ i_{in}$$

$$R_{out} = r_{DS}$$

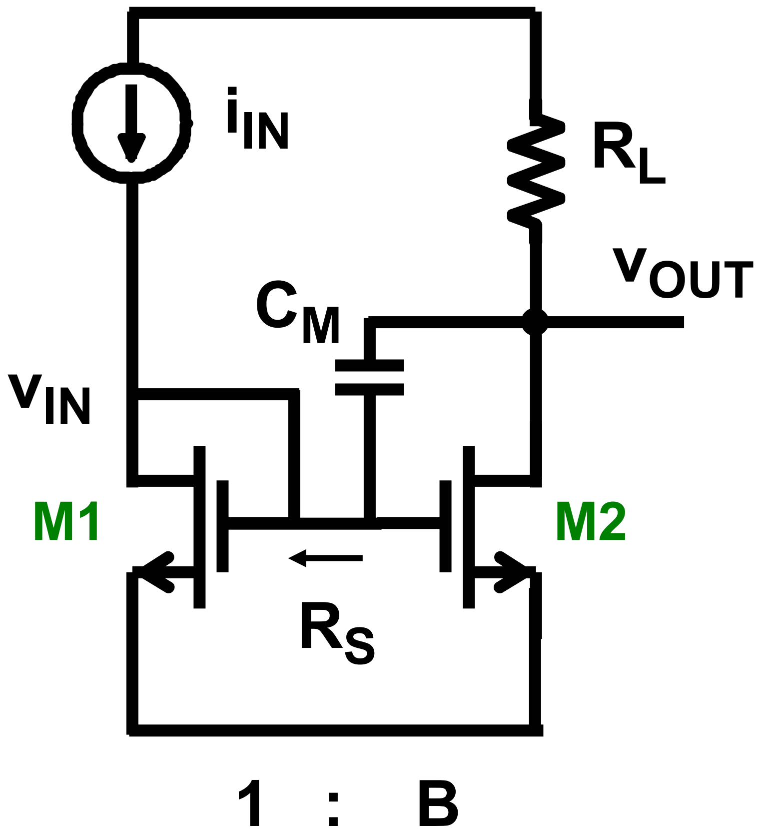
$$C_G = (1 + B)\ C_{GS} + C_{DS1}$$

$$BW = \frac{g_m}{2\pi\ (C_G + C_{DS1})}$$

$$\approx f_T \frac{1}{(2 + B)}$$

Ref.: Gilbert, JSSC Dec.68, 353-365

Current Miller effect



$A_i = B$

$R_{IN} = \frac{1}{g_{m1}}$

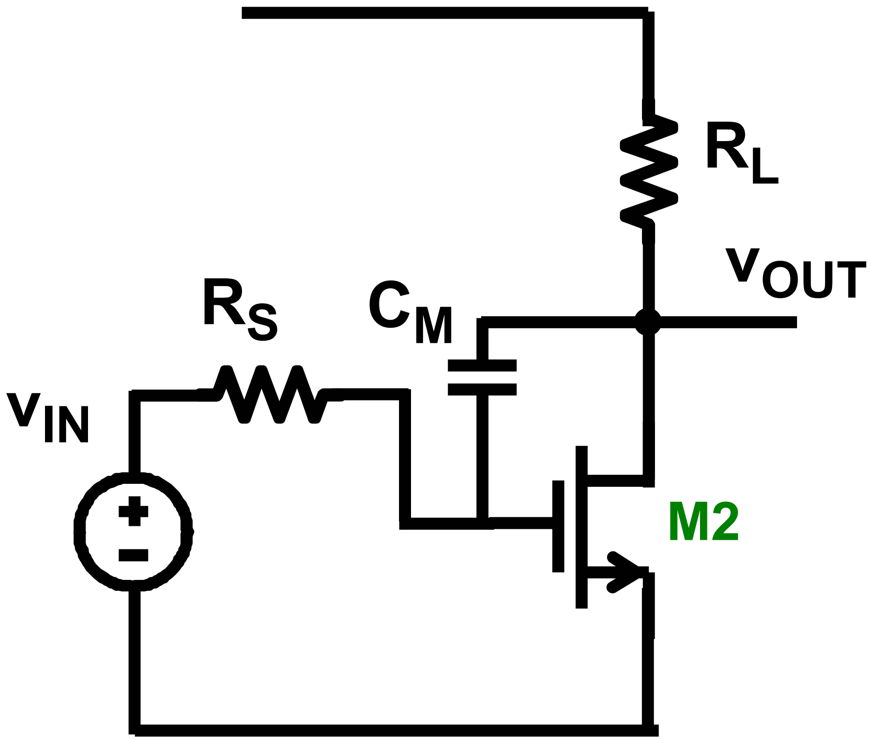
$R_S = 1/g_{m1}$

$v_{IN} \approx i_{IN} R_S$

$B = \frac{g_{m2}}{g_{m1}}$

Ref.: Rincon-Mora, JSSC Jan. 2000, 26-32

Current Miller equivalent circuit



Miller effect :

$$f_{-3dB} = \frac{1}{2\pi\, R_S A_{v2} C_M}$$

$R_S = 1/g_{m1}$ $\quad A_{v2} = g_{m2} R_L$

$$f_{-3dB} = \frac{1}{2\pi\, (1+B) C_M R_L}$$

$$f_z = -\frac{g_{m2}}{2\pi\, C_M}$$

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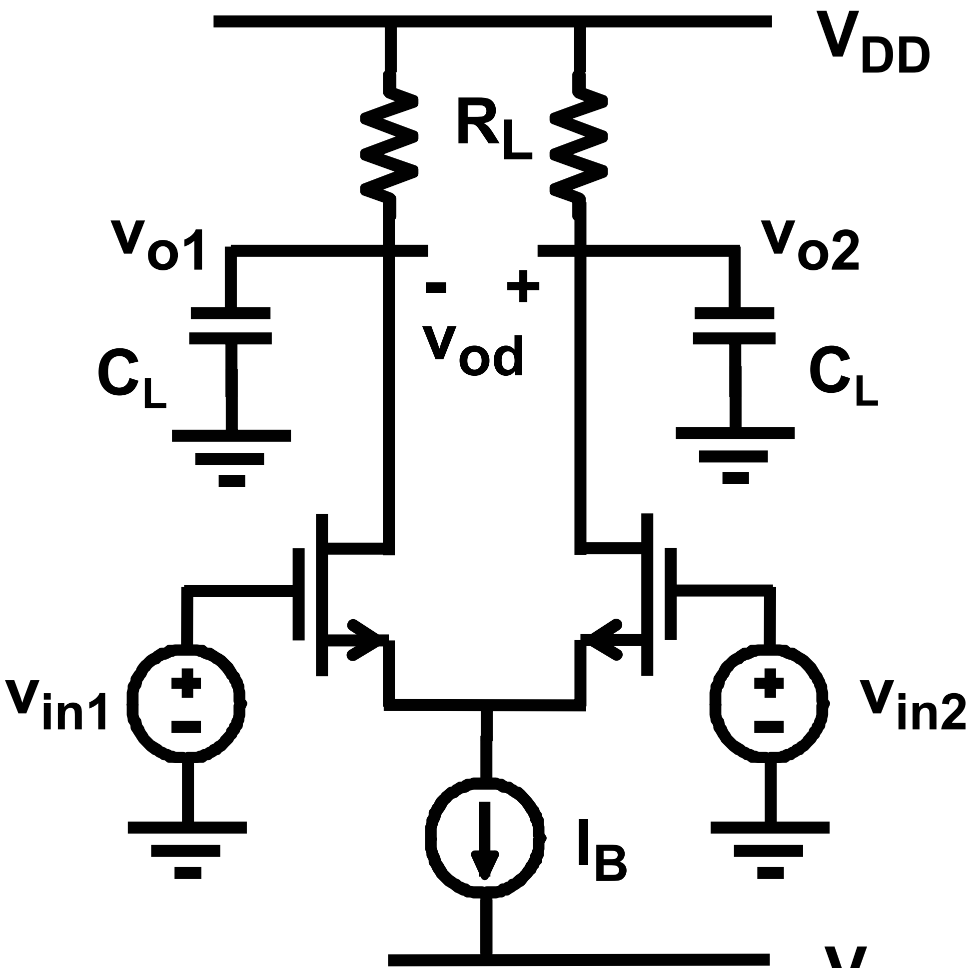
Voltage differential amplifier



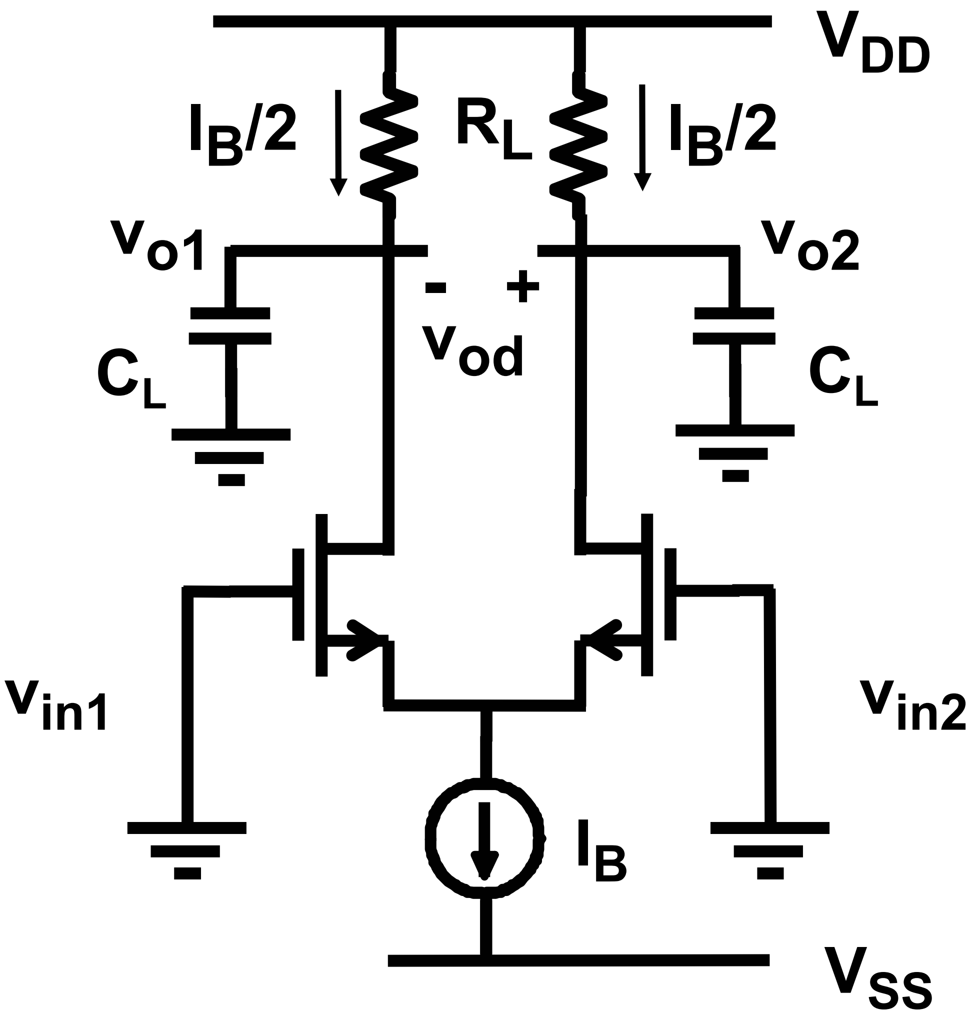
Two equal transistors

Redefine v_{in} & v_o :

$$\left[\begin{array}{l} v_{ind} = v_{in1} - v_{in2} \\ v_{inc} = \dfrac{v_{in1} + v_{in2}}{2} \end{array}\right.$$

$$\left[\begin{array}{l} v_{od} = v_{o1} - v_{o2} \\ v_{oc} = \ldots \end{array}\right.$$

Voltage differential amplifier : DC

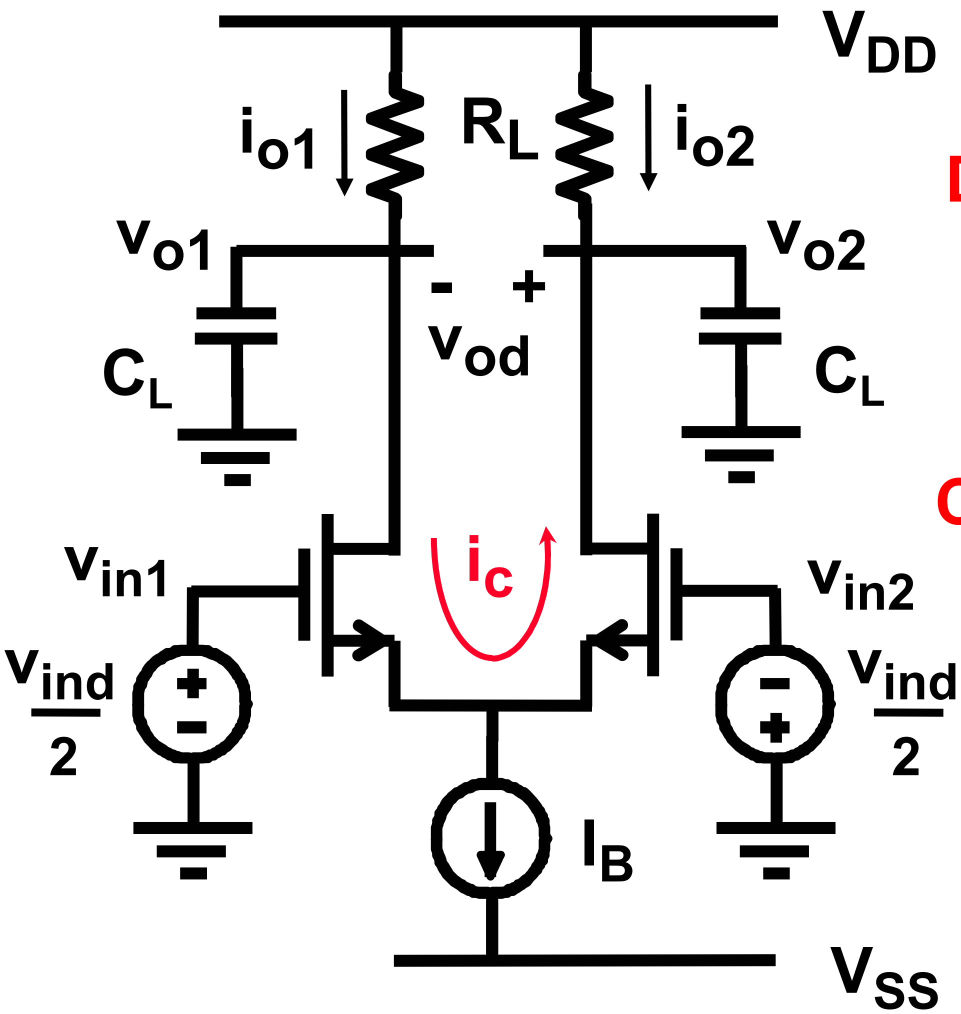


$$v_{in1} = v_{in2} = 0$$

$$v_{o1} = v_{o2}$$
$$= V_{DD} - R_L\, I_B/2$$

$$v_{od} = v_{o1} - v_{o2} = 0$$

Voltage differential amplifier : AC Gain



Differential input voltage

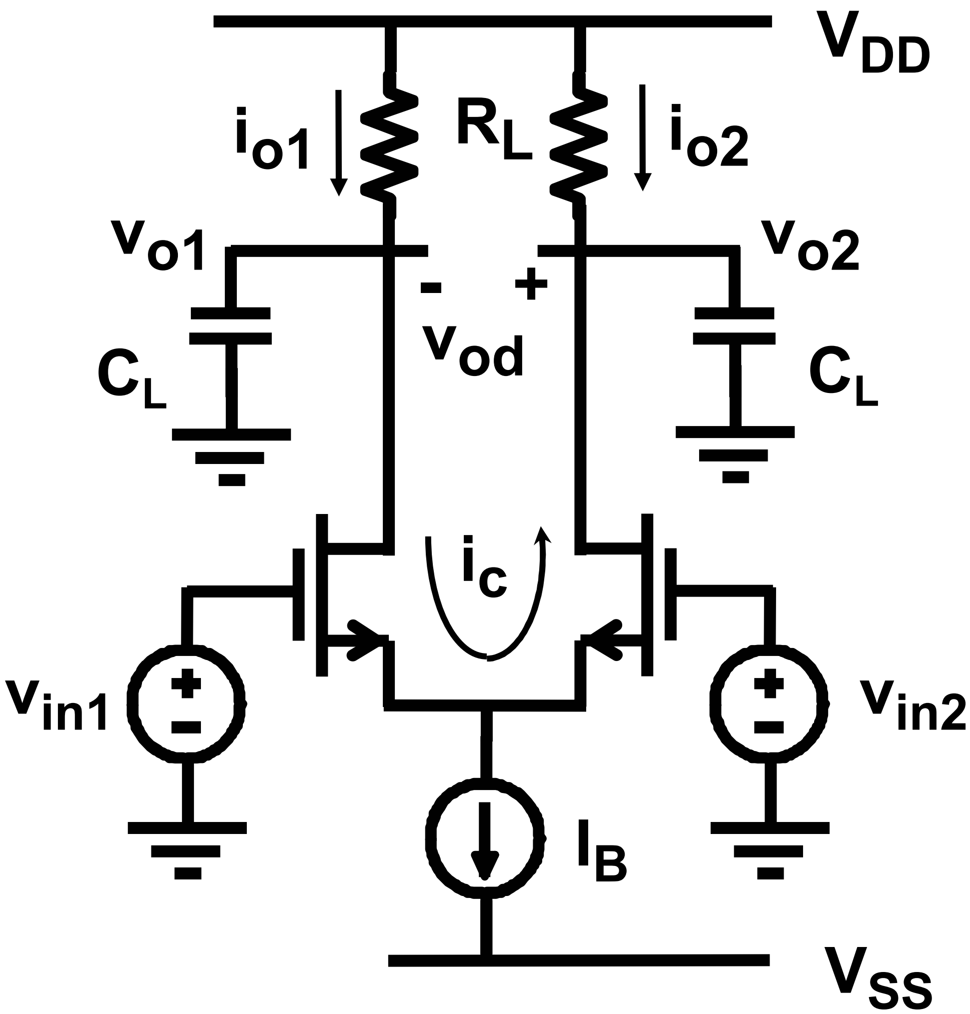
$$v_{ind} = v_{in1} - v_{in2}$$

Circular current $i_c = g_m \frac{v_{ind}}{2}$

$$v_{od} = 2\,R_L\,i_c$$

$$A_v = \frac{v_{od}}{v_{ind}} = g_m R_L$$

Voltage differential amplifier



$A_v = g_m R_L$

Same as single-tr. !!

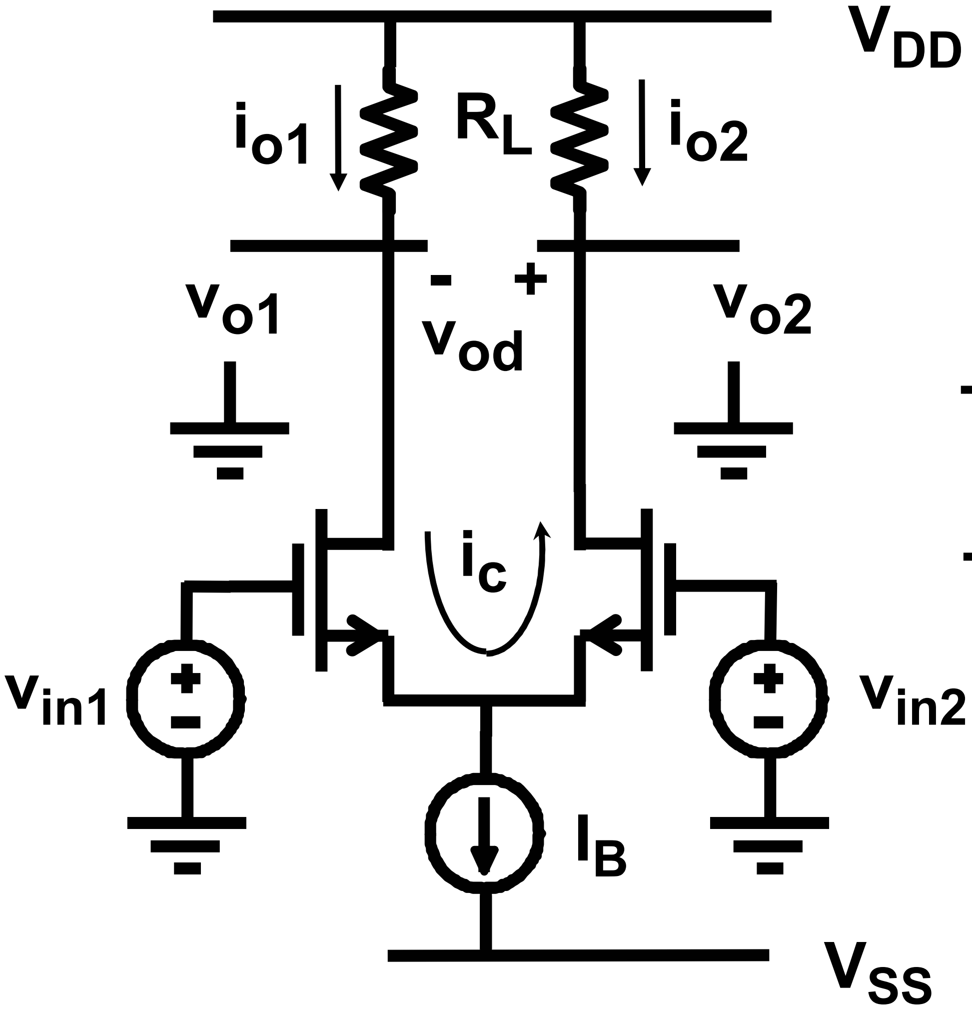
Independent of :

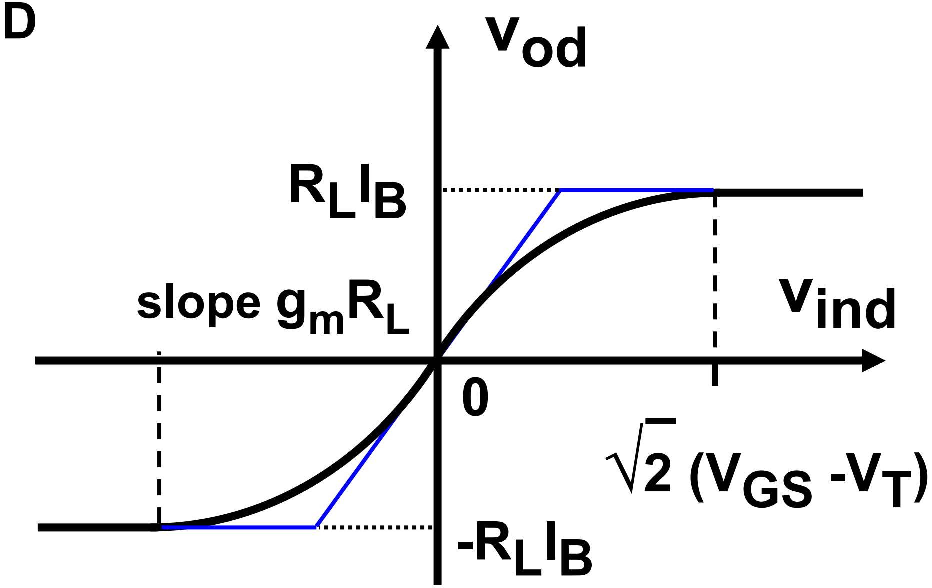
Noise on V_{DD} : $PSRR_{DD}$

Noise on V_{SS} : $PSRR_{SS}$

Noise on Ground : CMRR

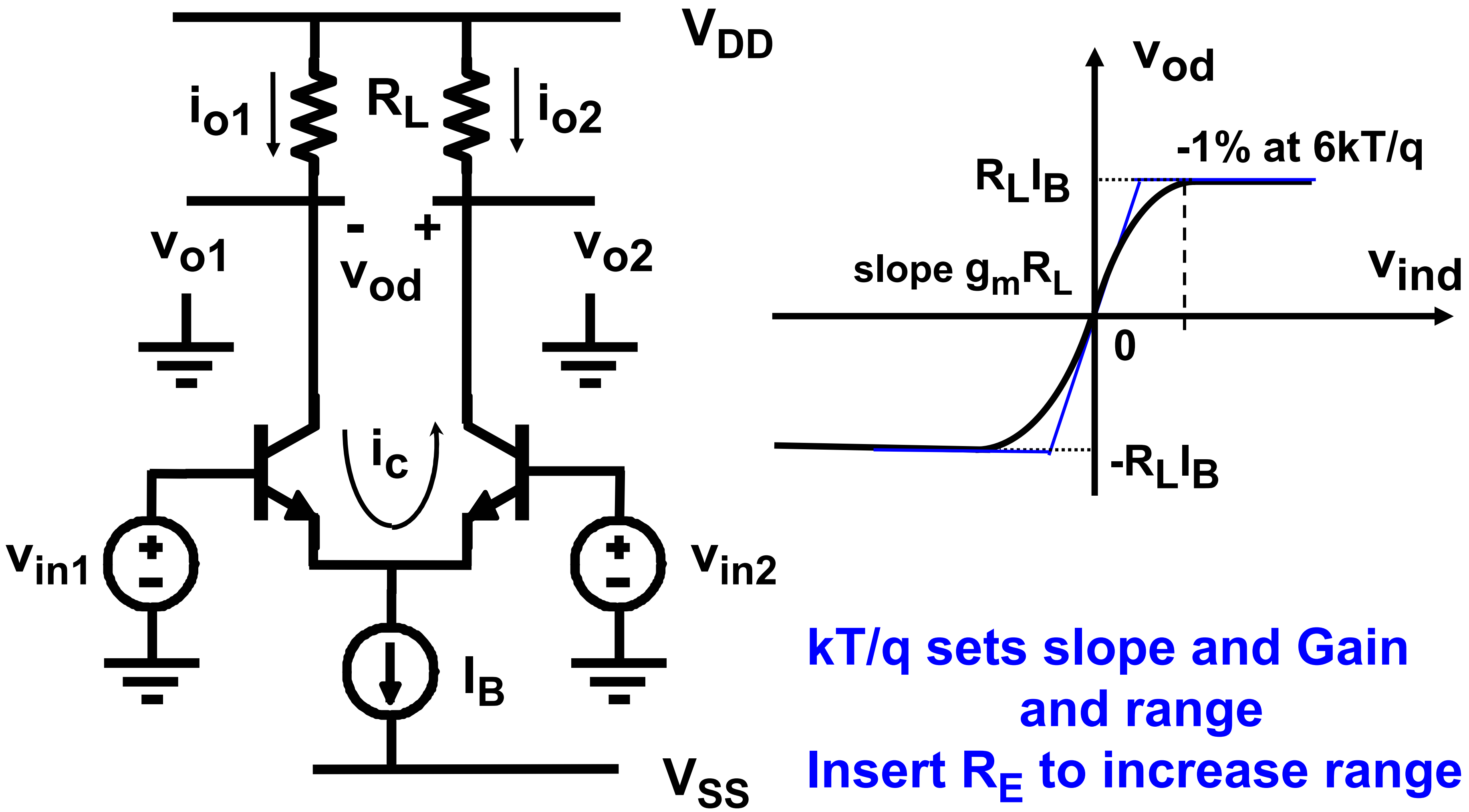
CMOS Voltage differential amplifier : DC range





$V_{GS} - V_T$ sets slope
and range
and …. Gain !

Bipolar Voltage diff. amplifier : DC range



kT/q sets slope and Gain and range

Insert R_E to increase range !

MOST Voltage diff. amplifier : large input signals

$$\frac{i_{Od}}{I_B} = \frac{v_{Id}}{(V_{GS}-V_T)} \sqrt{1 - \frac{1}{4} \left(\frac{v_{Id}}{V_{GS}-V_T} \right)^2}$$

v_{Id} is the differential input voltage

i_{Od} is the differential output current ($g_m v_{Id}$) or
twice the circular current $g_m v_{Id}$ /2

I_B is the total DC current in the pair

Note that $g_m = \frac{I_B}{V_{GS} - V_T} = K' \, W/L \, (V_{GS} - V_T)$

Bipolar Voltage diff. amp. : large input signals

$$\frac{i_{Od}}{I_B} = \tanh \frac{v_{Id}}{2\,kT/q}$$

$$\tanh x = \frac{e^x - e^{-x}}{e^x + e^{-x}} = \frac{2e^x - 1}{2e^x + 1}$$

v_{Id} is the differential input voltage

i_{Od} is the differential output current ($g_m v_{Id}$) or

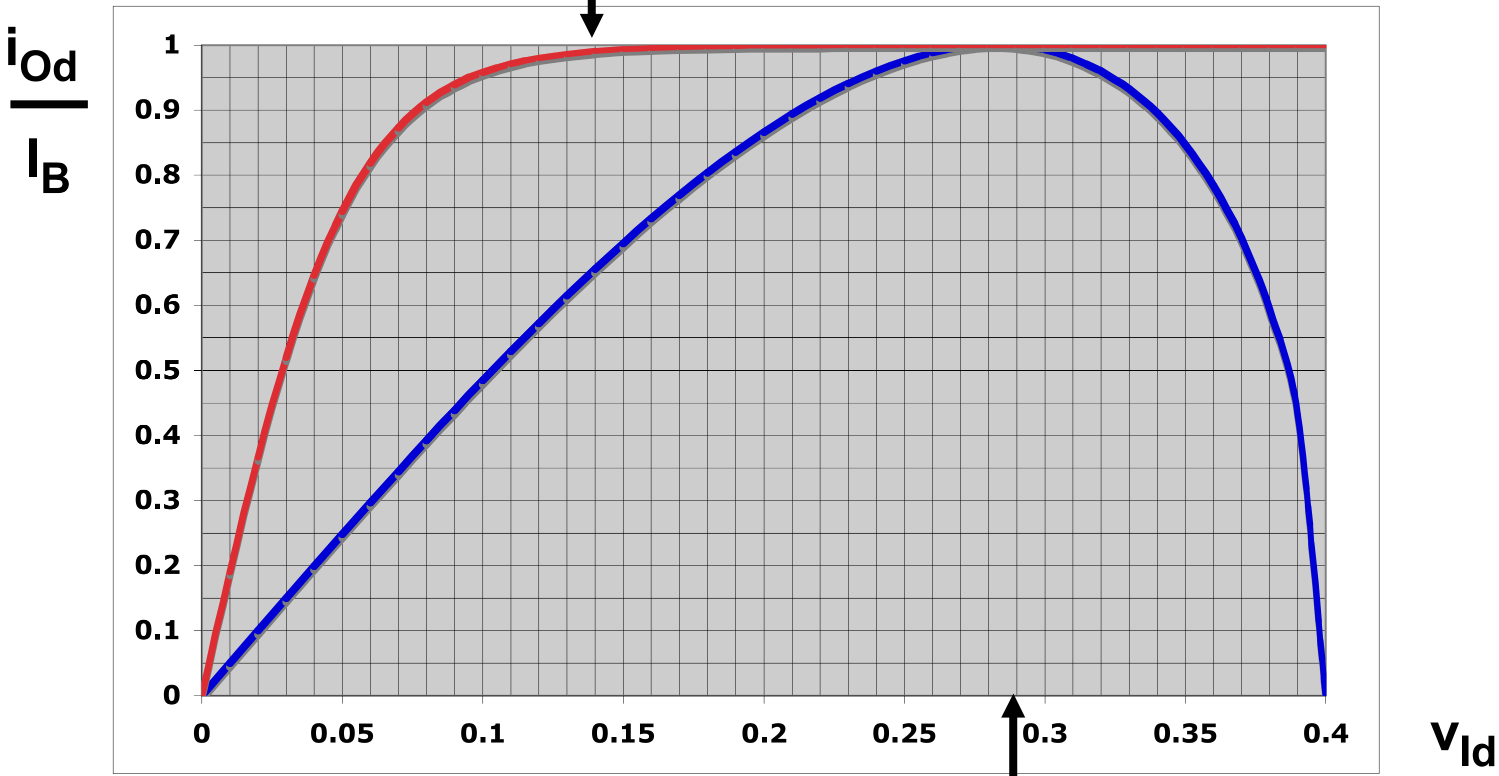
twice the circular current $g_m v_{Id}$ /2

I_B is the total DC current in the pair

Note that $g_m = \dfrac{I_B}{2\,kT/q}$

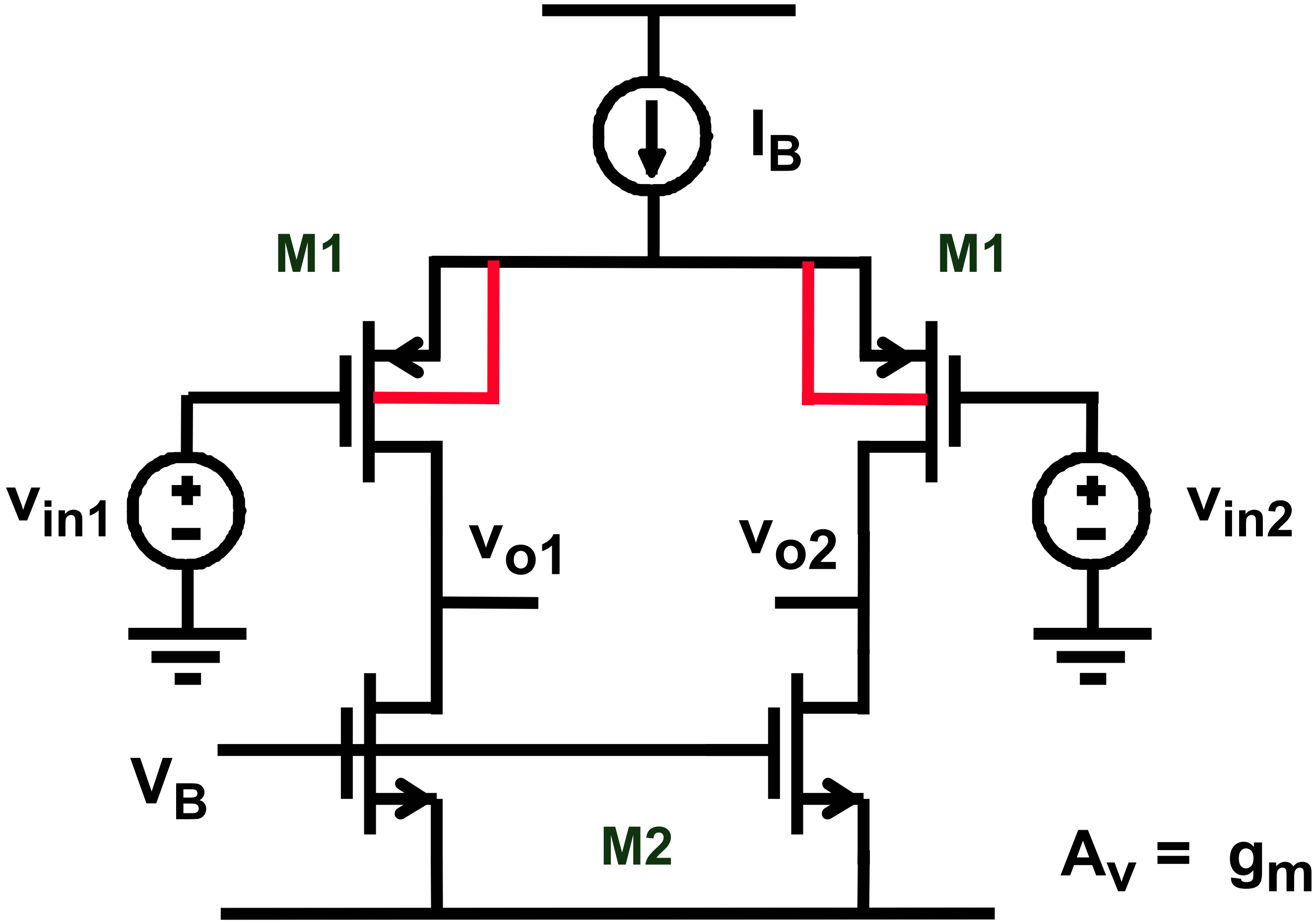
Voltage differential amplifier: transfer function

-1% $V_{Id} \approx 2.67 \times 2kT/q = 0.14$ V



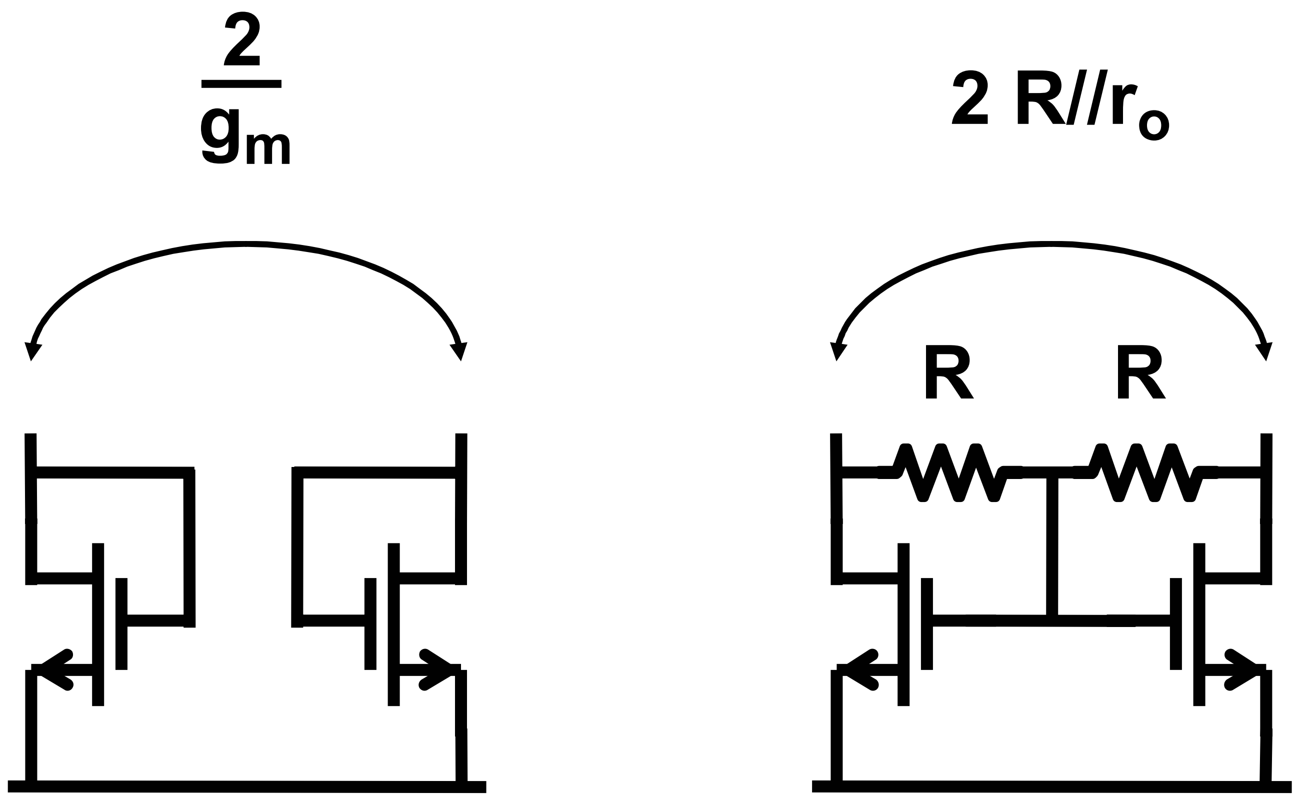
$V_{Id} = \sqrt{2}\,(V_{GS}-V_T) = \sqrt{2} \times 0.2$ V

Voltage differential amplifier with $g_m r_{DS}$ gain

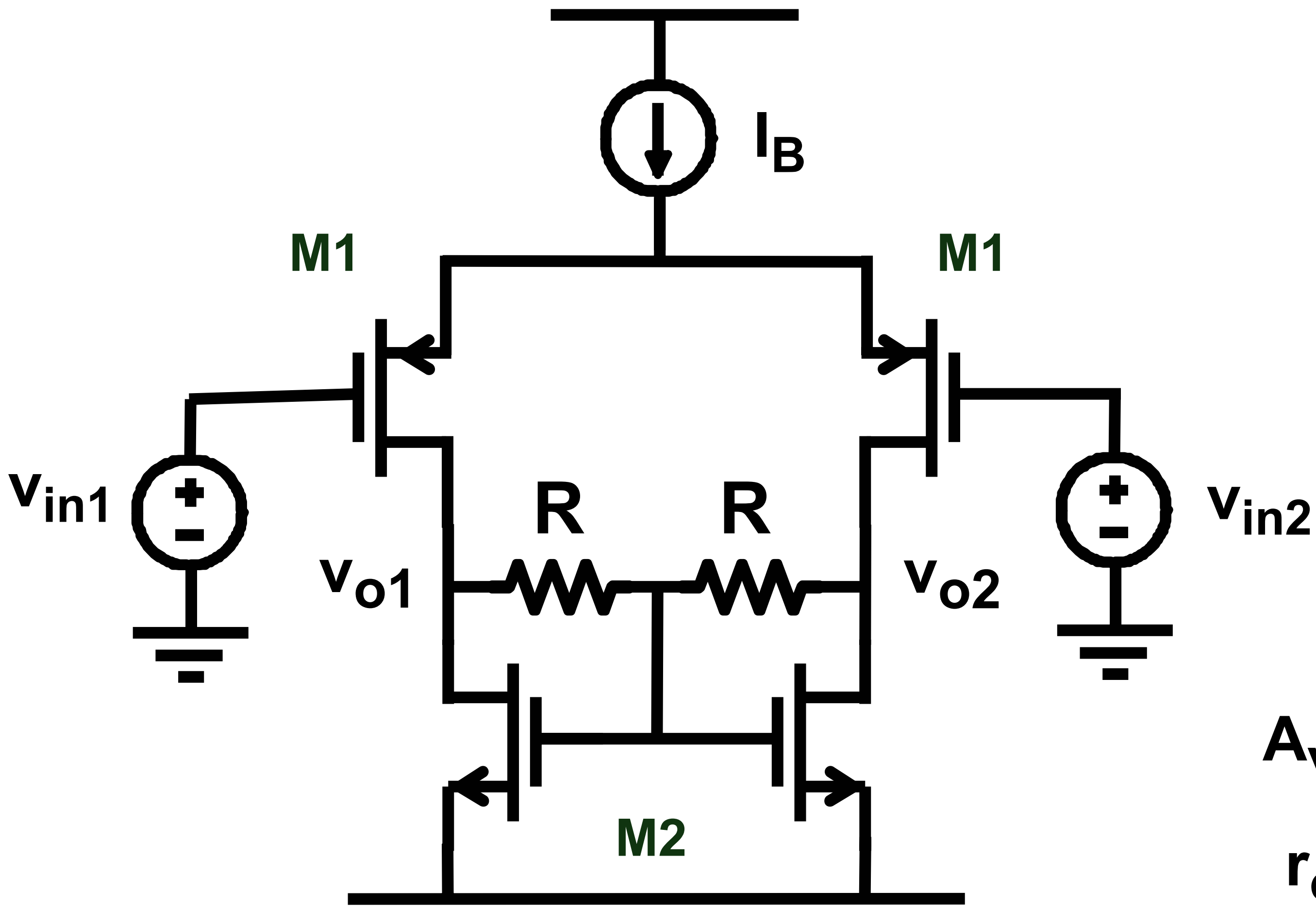


$A_v = g_{m1}(r_{DS1}//r_{DS2})$

Diode-connected MOSTs with resistors



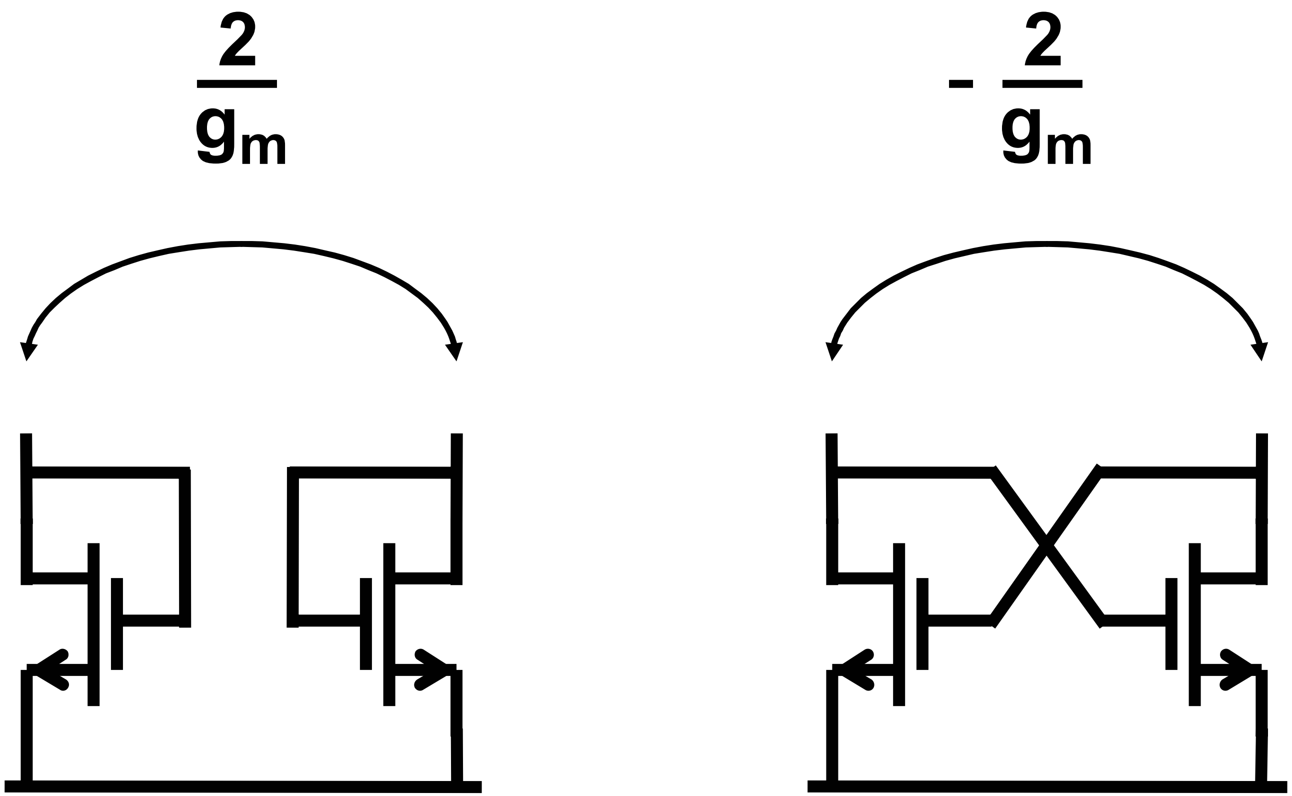
Voltage differential amplifier with high gain



$A_v = g_{m1}\,(R \,//\, r_o)$

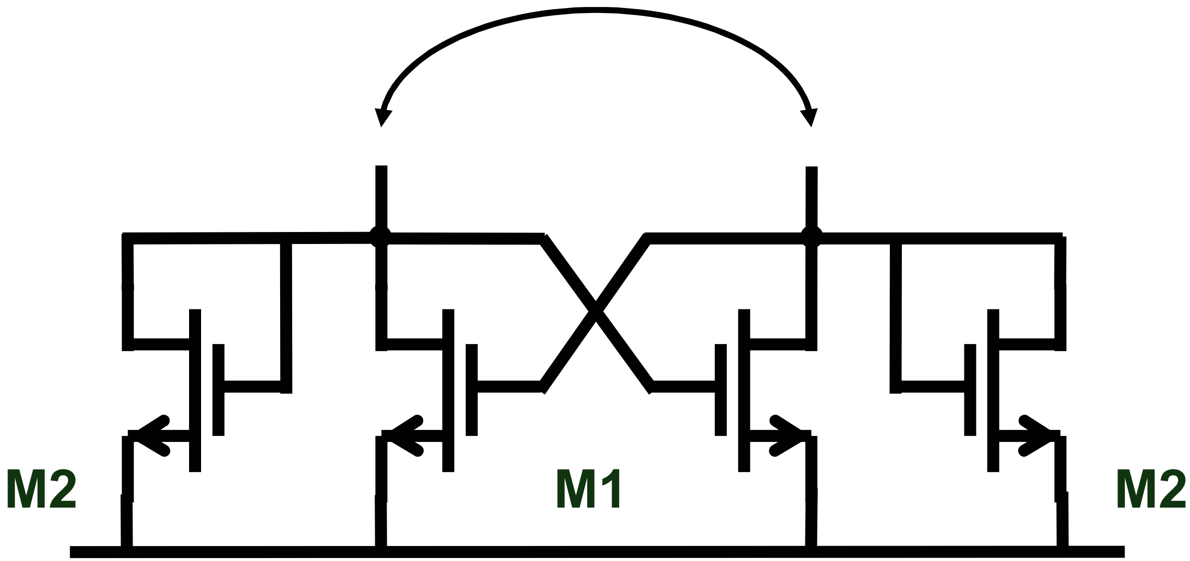
$r_o = r_{o1} // r_{o2}$

Differential diode-connected MOSTs



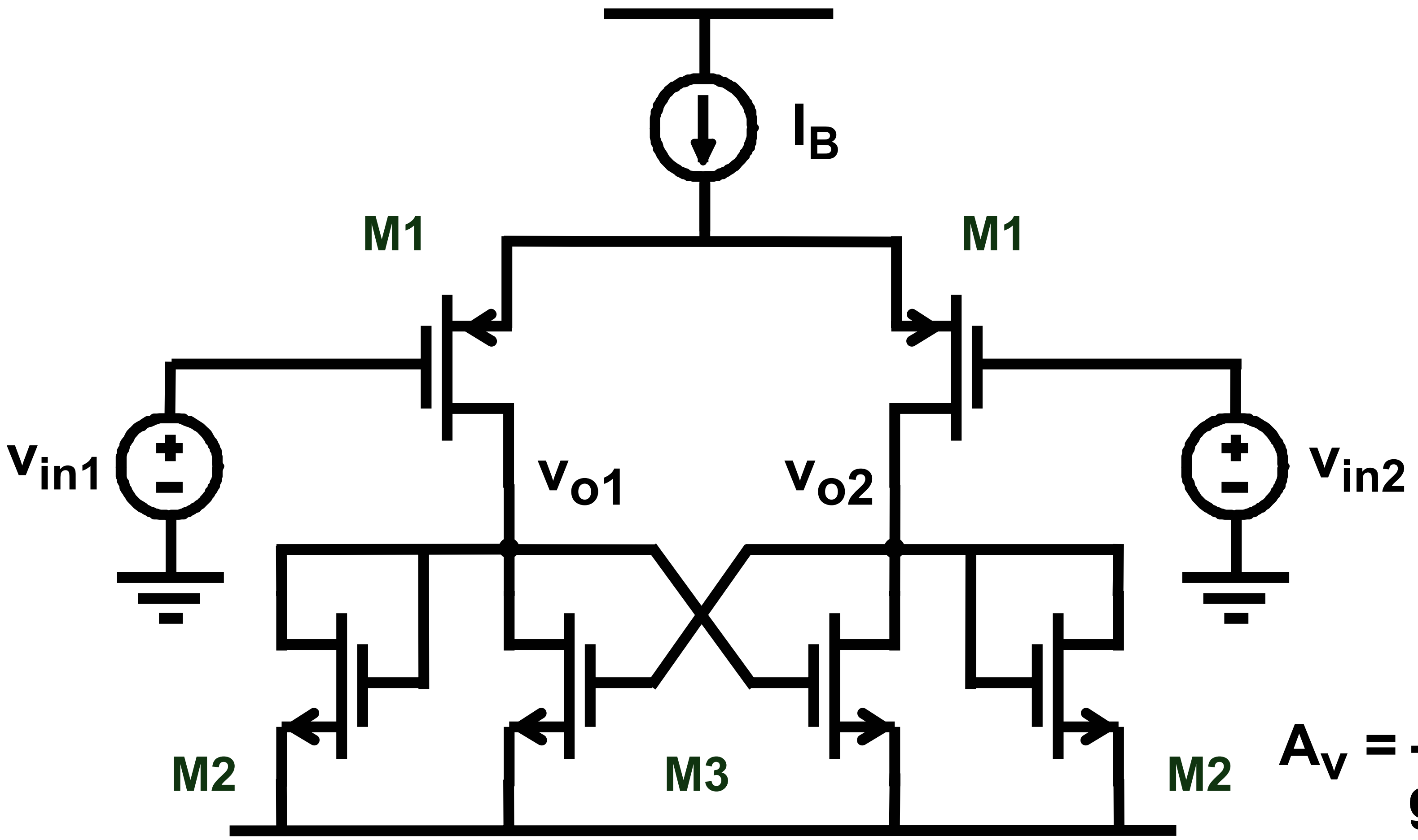
Differential diode-connected MOSTs

$$\frac{2}{g_{m2} - g_{m1}}$$



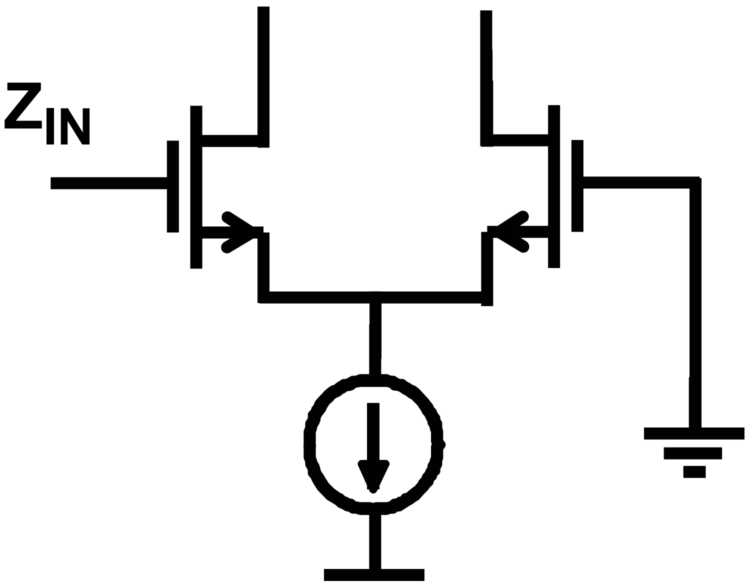
Values close to ∞ !

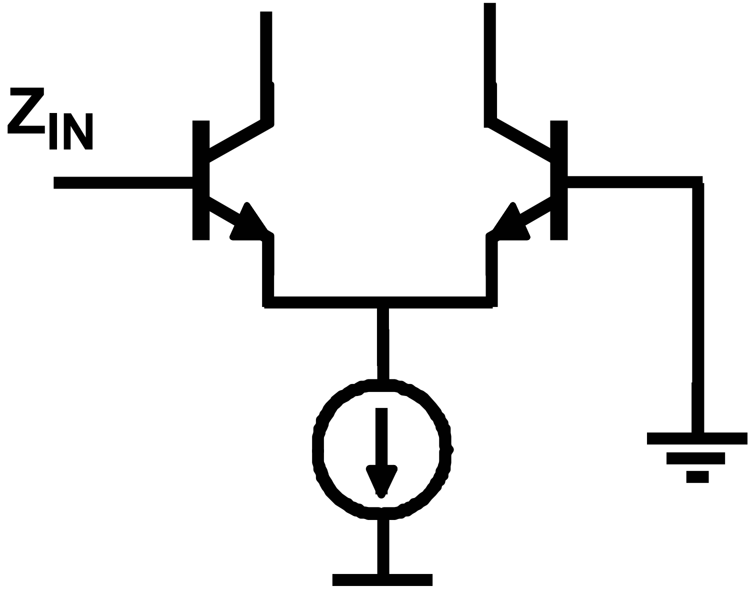
High gain because of current cancellation



$$A_v = \frac{g_{m1}}{g_{m2} - g_{m3}}$$

Input impedance

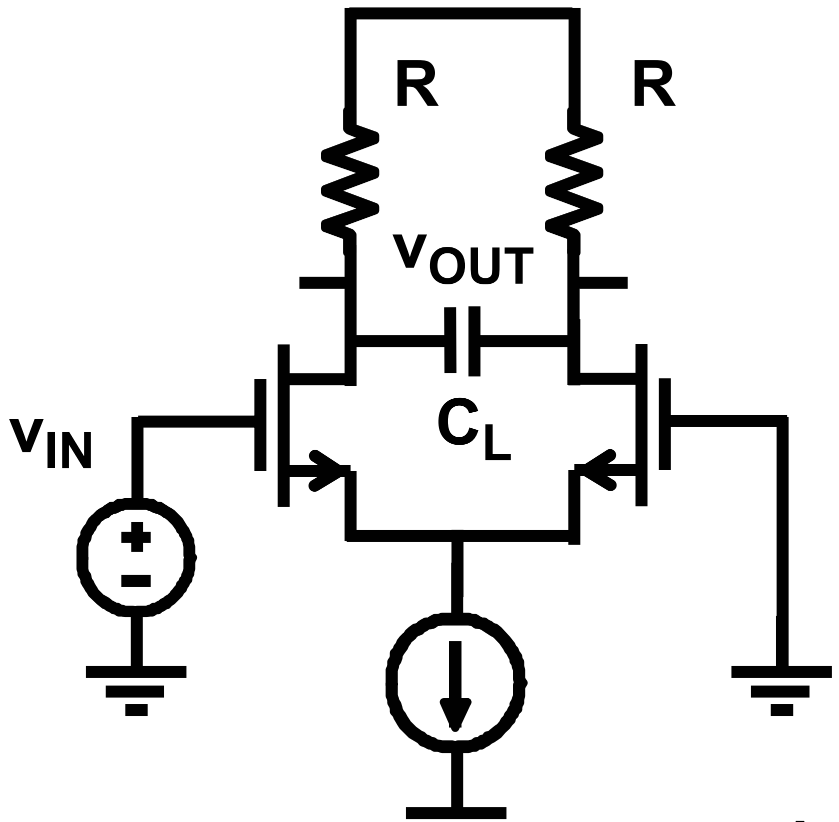


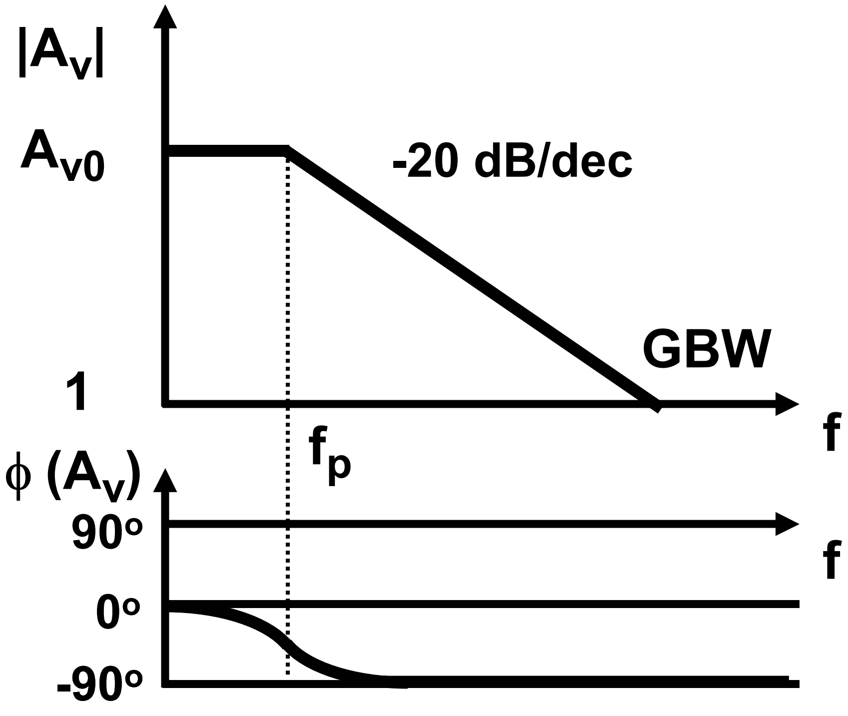


$$C_{IN} = \frac{C_{GS}}{2}$$

$$R_{IN} = 2\, r_{\pi} \qquad C_{IN} = \frac{C_{\pi}}{2}$$

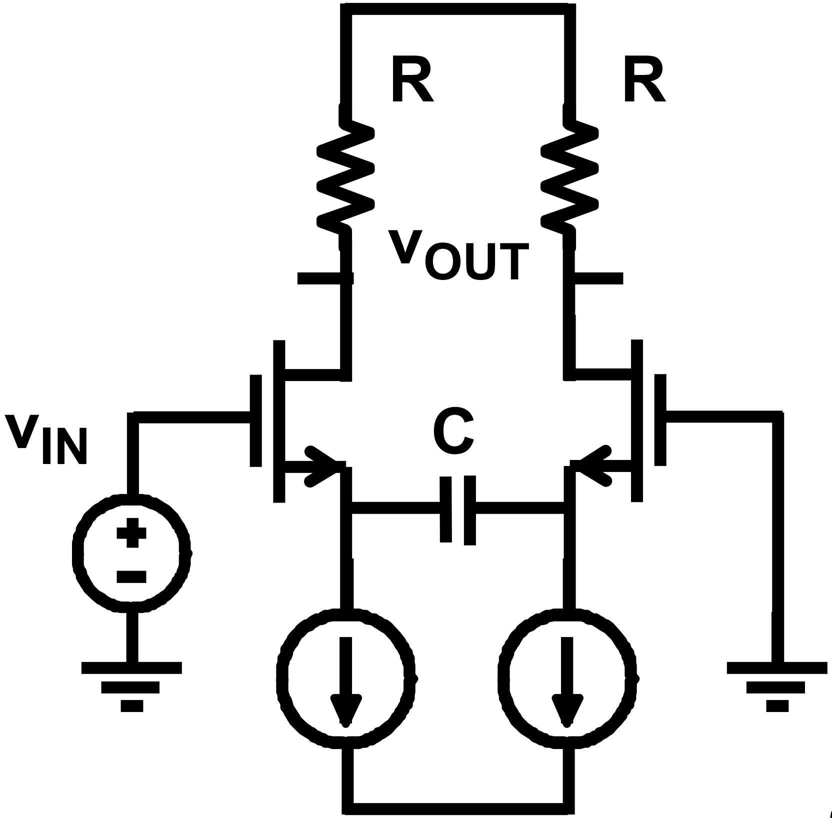
Low-Pass Voltage Differential amplifier

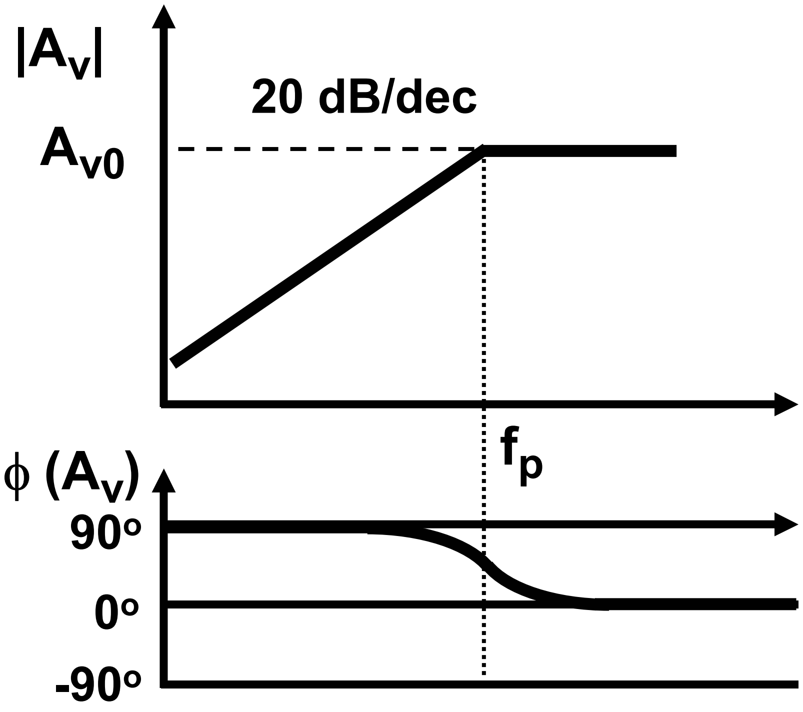




$$A_{v0} = g_m R \qquad A_V = \frac{A_{v0}}{(1 + j\frac{f}{f_p})} \qquad f_p = \frac{1}{2\pi\, 2RC_L} \qquad GBW = \frac{g_m}{2\pi\, 2C_L}$$

High-Pass voltage differential amplifier



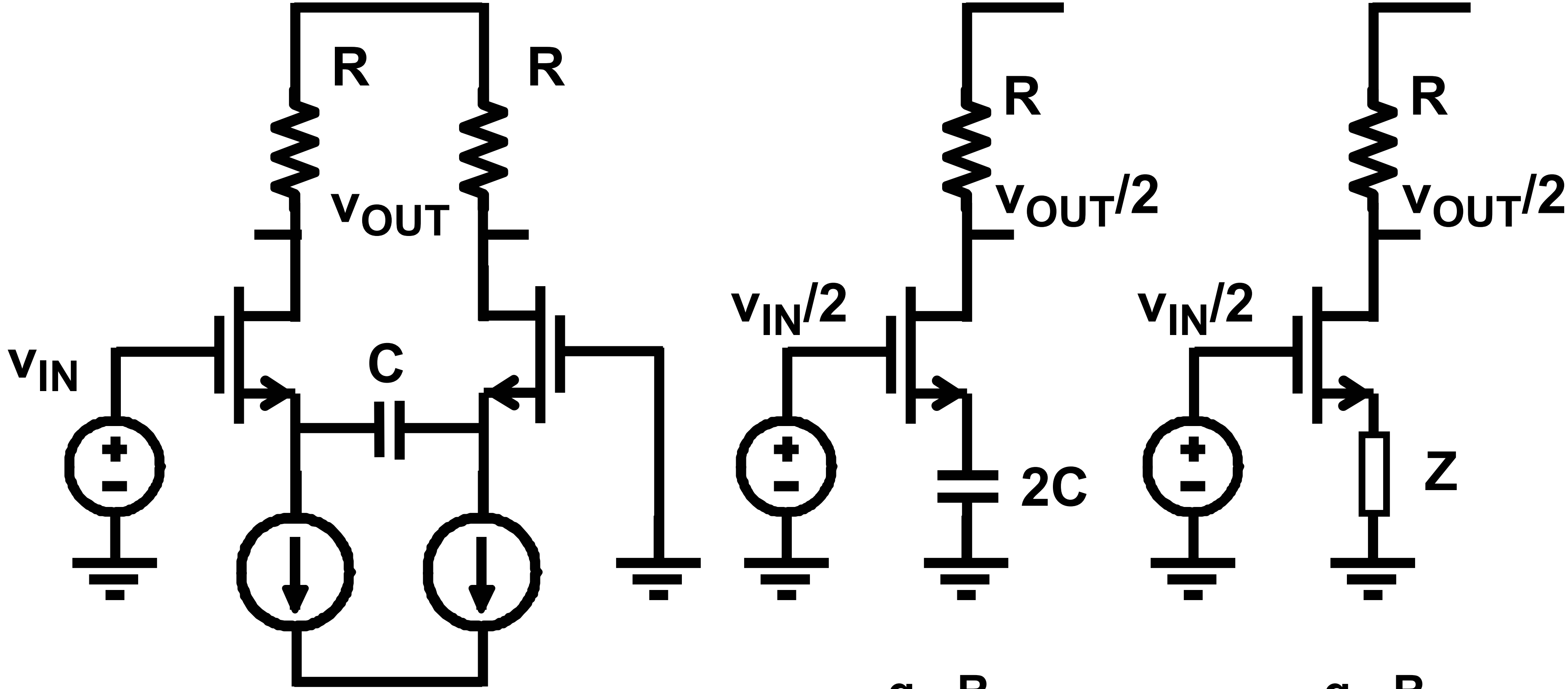


$$A_{v0} = g_m R$$

$$A_v = A_{v0} \frac{j \frac{f}{f_p}}{(1 + j \frac{f}{f_p})}$$

$$f_p = \frac{g_m}{2\pi\, 2C}$$

Calculation High-Pass differential amplifier



$$A_v = \frac{-\,g_m R}{\left(1 + \frac{g_m}{2Cs}\right)}$$

$$A_v = \frac{-\,g_m R}{1 + g_m Z}$$

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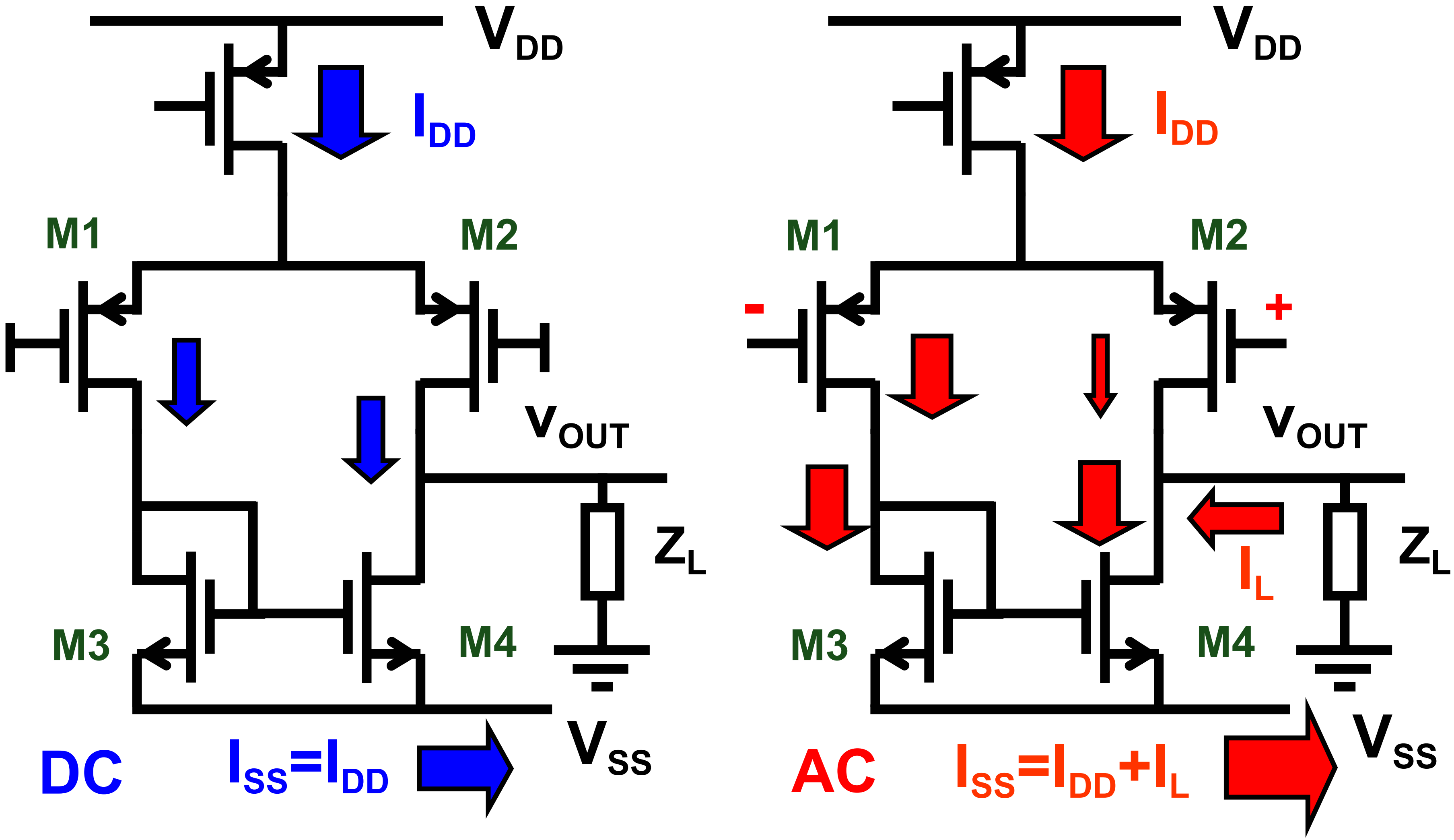
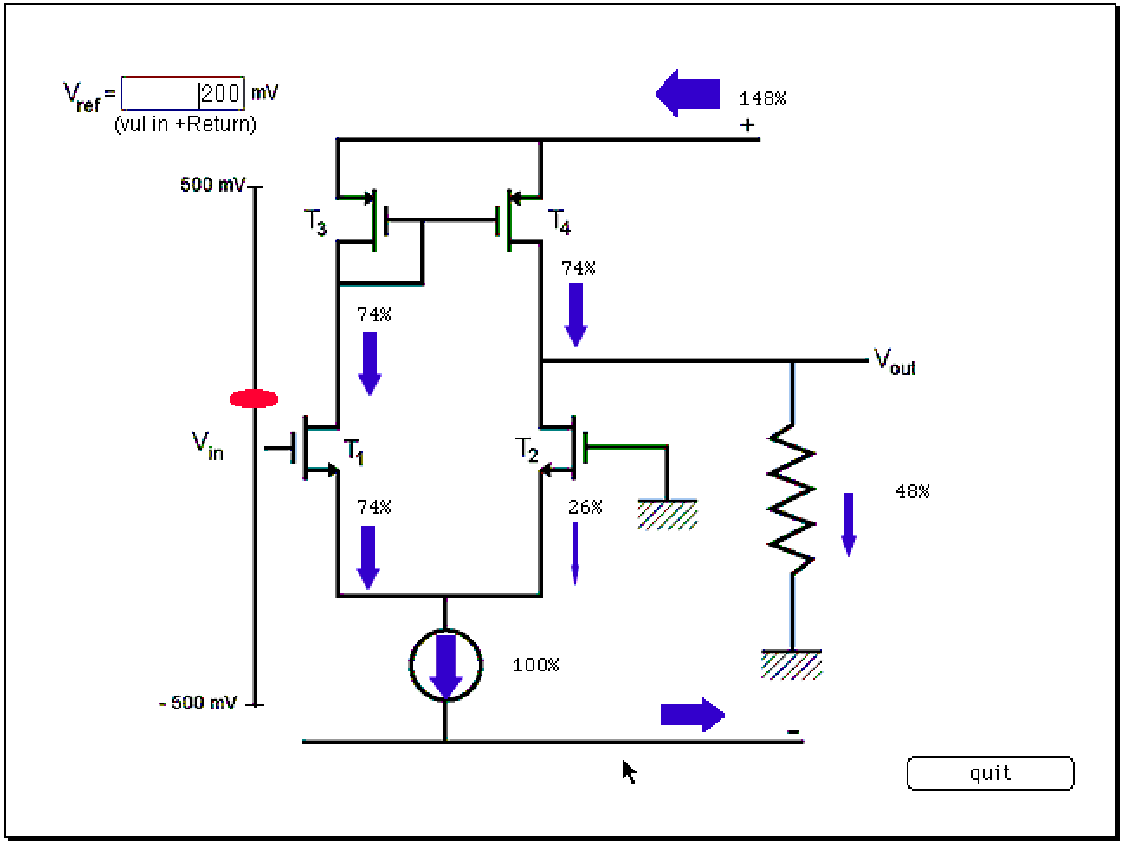
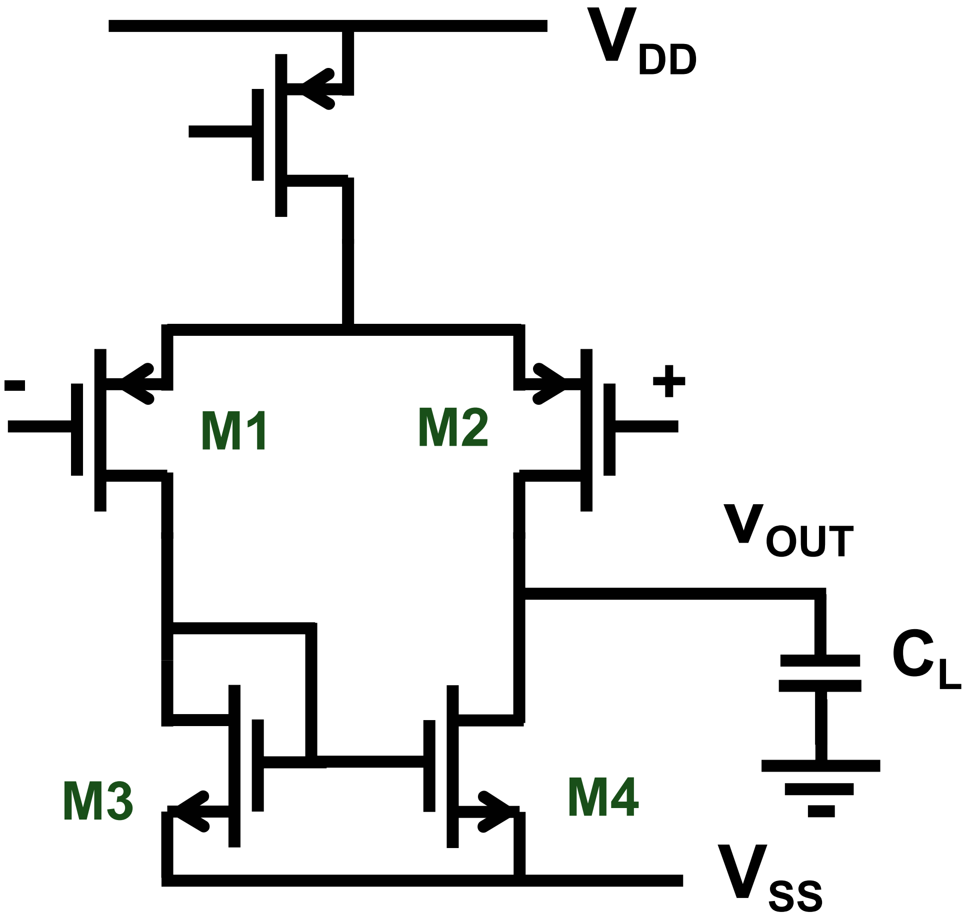
Operational Transconductance Amplifier (OTA)



Single-stage OTA: operation



Single-stage OTA



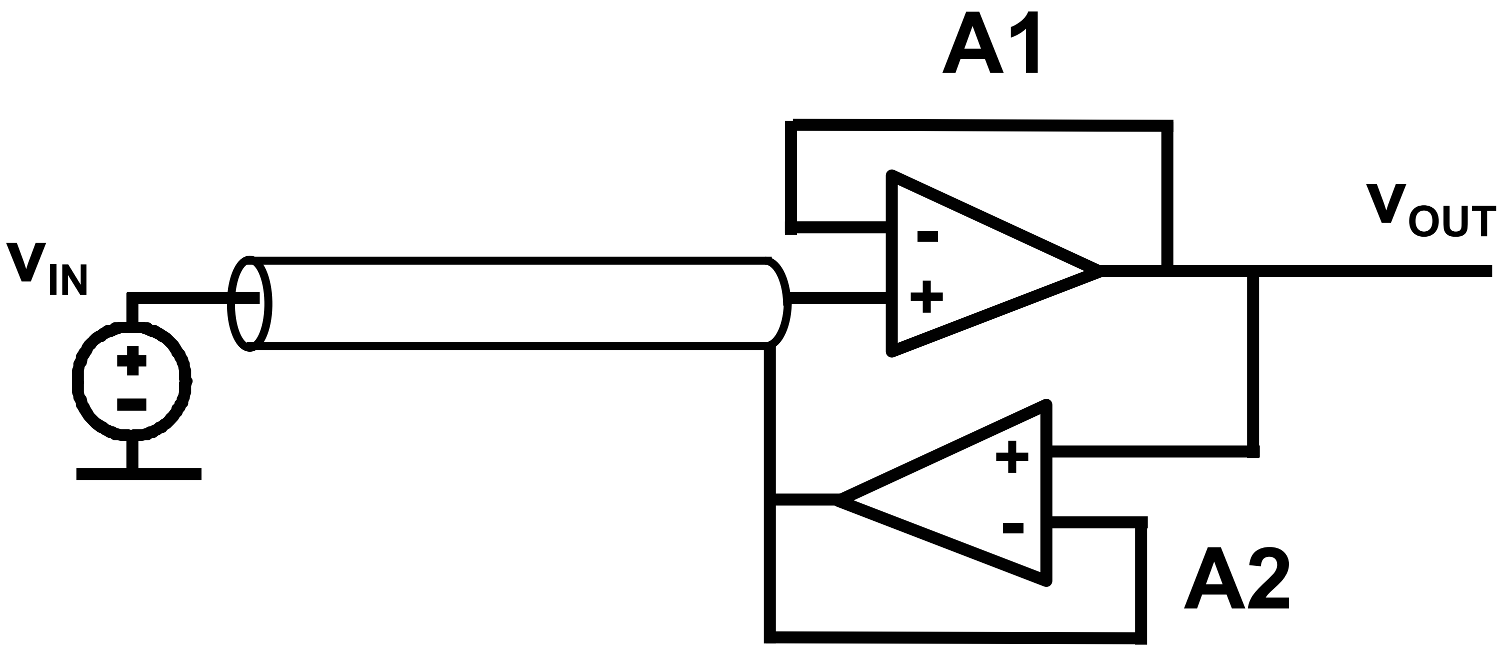
$$A_v = g_{m1} R_{out}$$

$$R_{out} = r_{DS2} \; // \; r_{DS4}$$

$$BW = \frac{1}{2\pi R_{out} C_L}$$

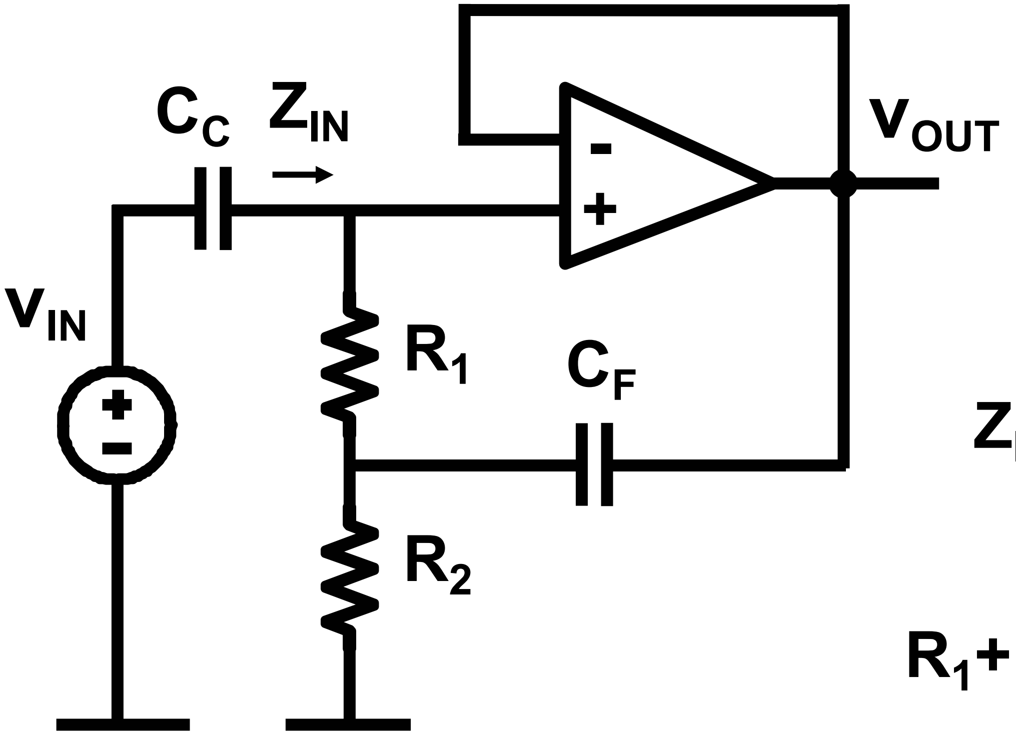
$$GBW = \frac{g_{m1}}{2\pi C_L}$$

Bootstrapping for low input capacitance



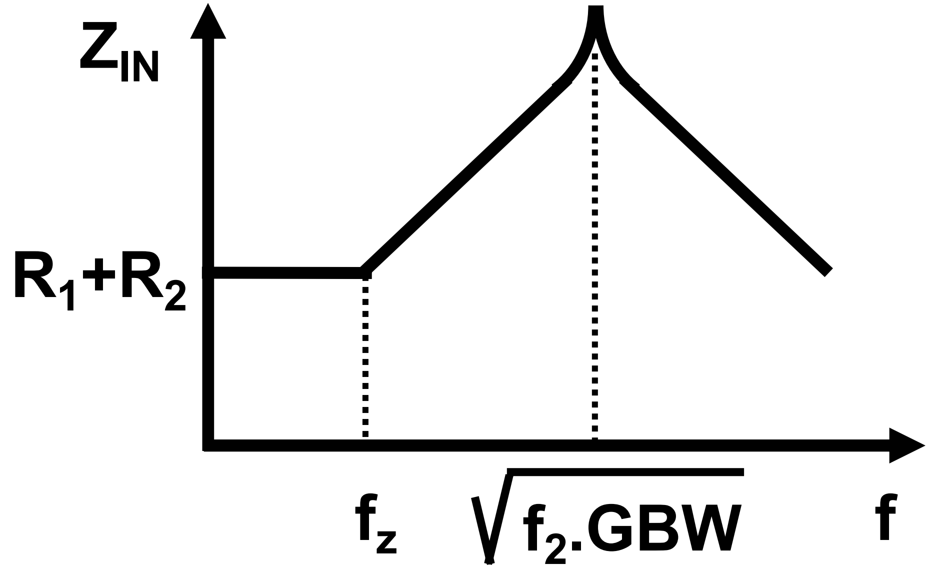
$C_{coax} \approx 0$!!!

Bootstrapping for high input impedance

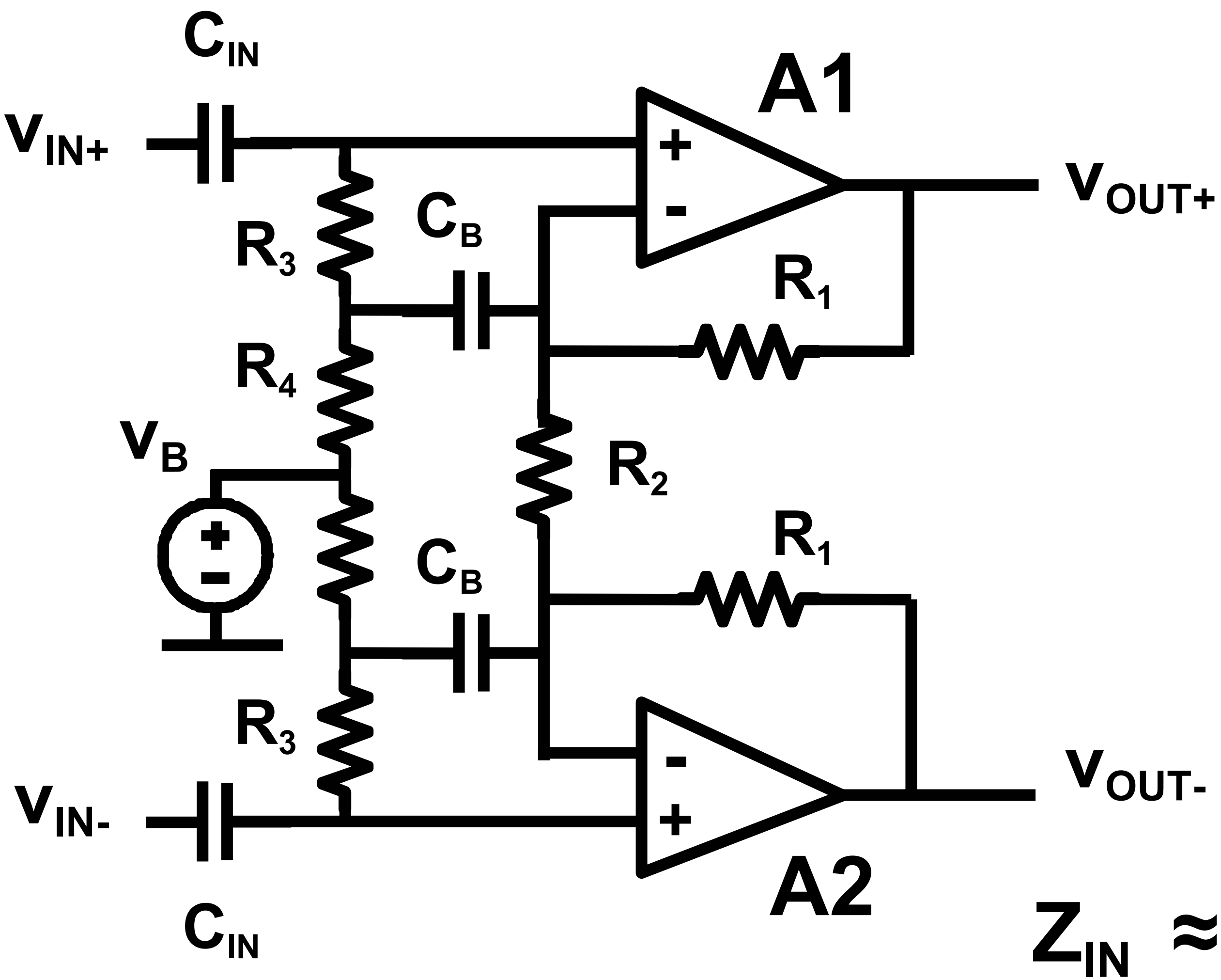


$$f_z = \frac{1}{2\pi\,(R_1+R_2)C_F}$$

$$f_2 = \frac{1}{2\pi\,R_2C_F}$$

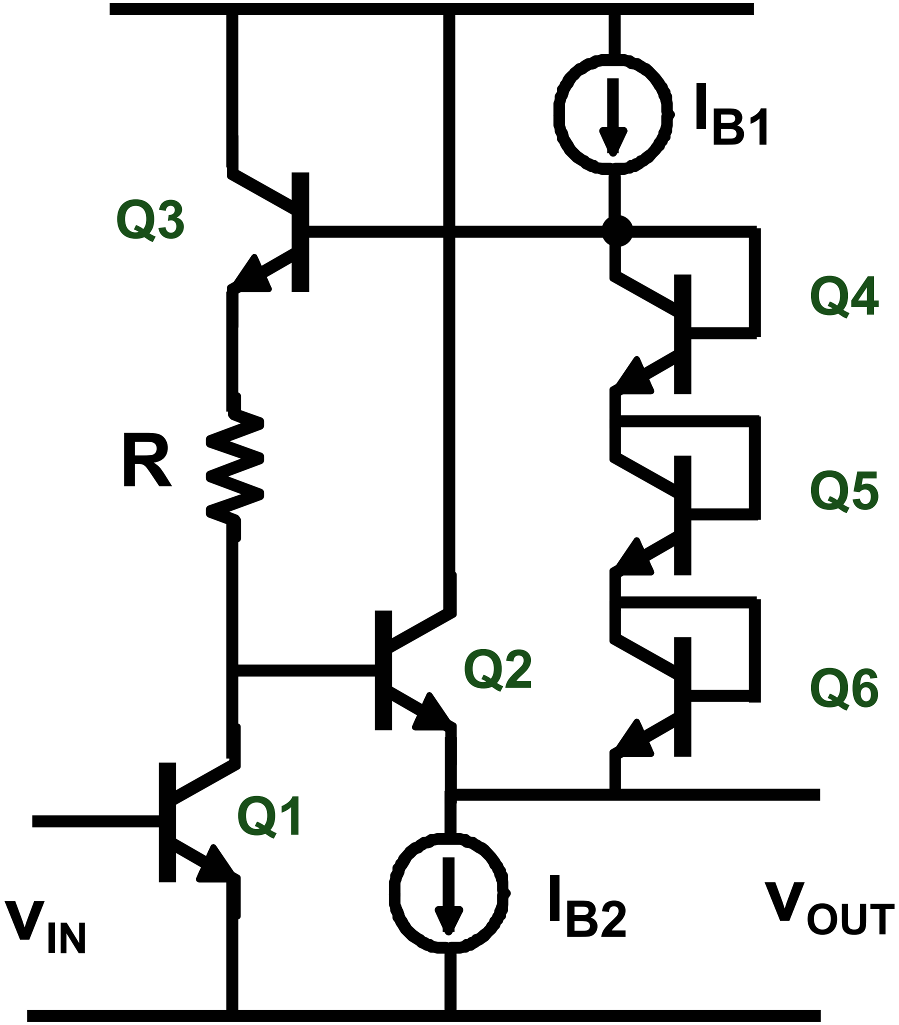


Bootstrapping for high input impedance



$Z_{IN} \approx \infty$!!!

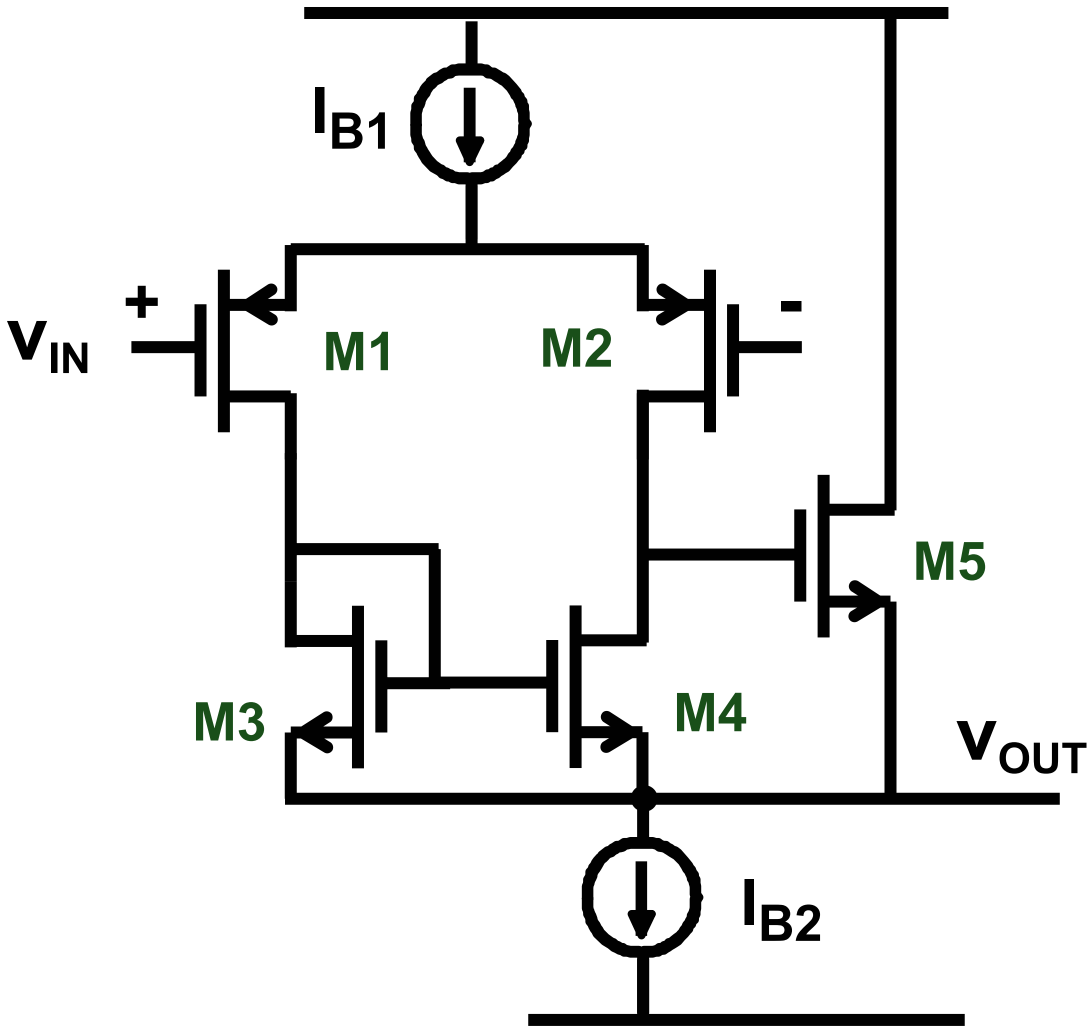
Bootstrapping out a load resistance R



R is bootstrapped out :
Very high gain !

Ref.: Nordholt
JSSC June 85, 688-696

Bootstrapping out an output resistance

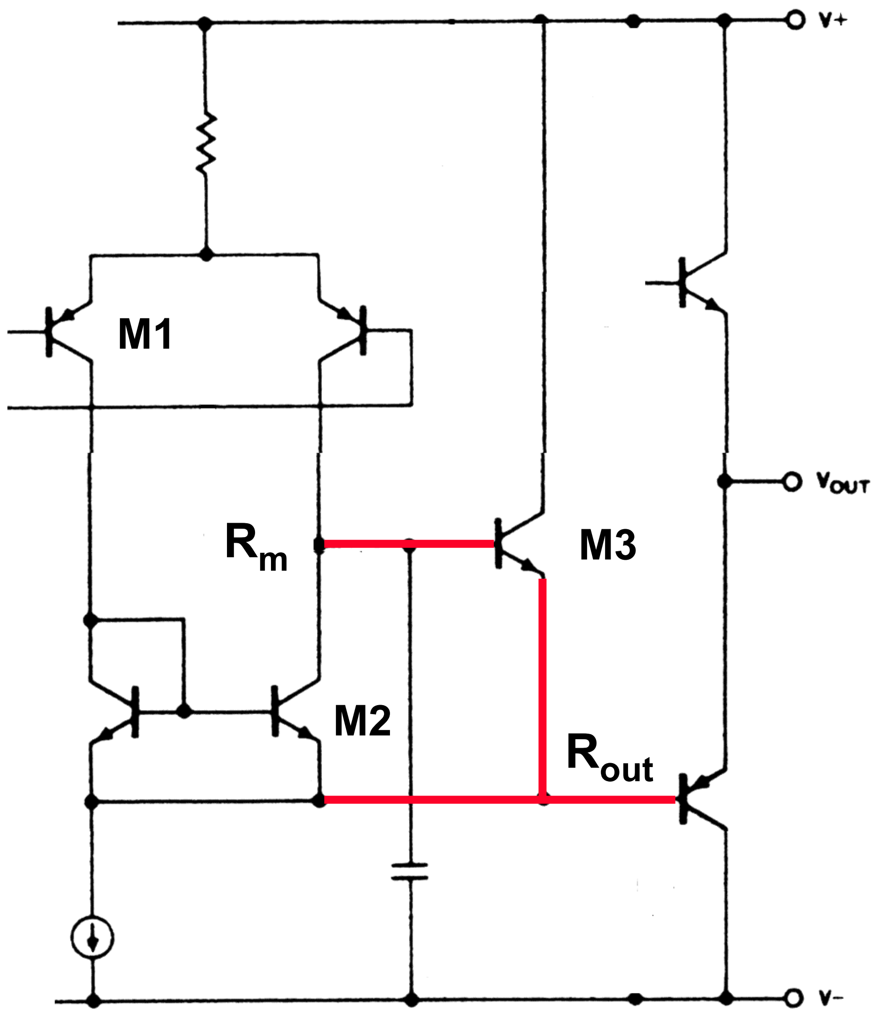


r_{o4} is bootstrapped out !

$A_v \approx g_{m1} r_{o2}$

Same GBW !

Bootstrap for high gain A_{v2}



R_m -> x β_3

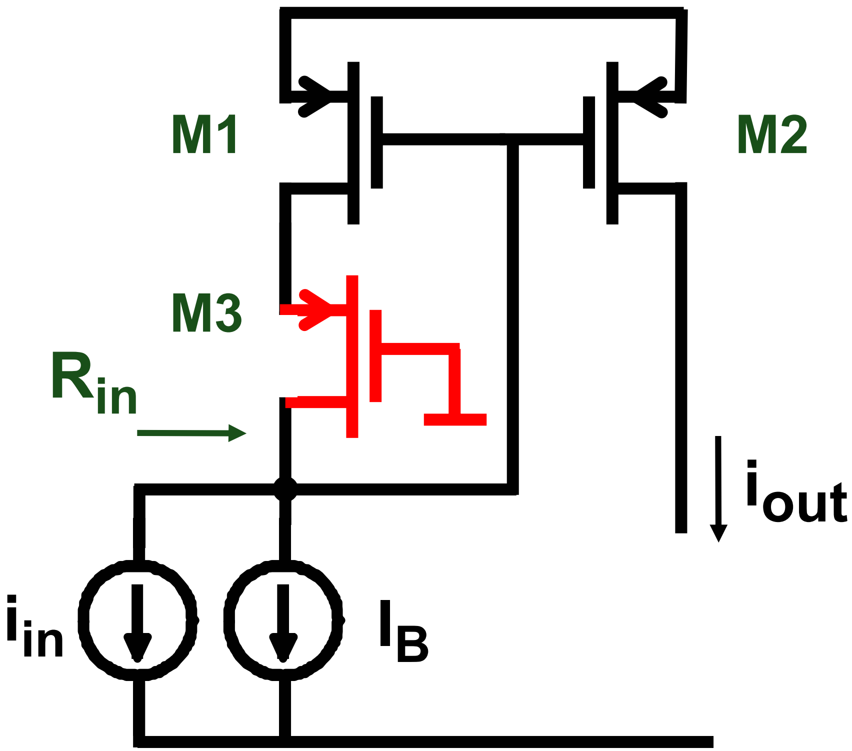
R_{out} -> x $\frac{1}{\beta_3}$

$A_{v2} \approx g_{m1}\, r_{o2} \times \beta_3$

Same GBW !

Ref.De Man JSSC June 77, pp. 217-222
LT1008, LT1012

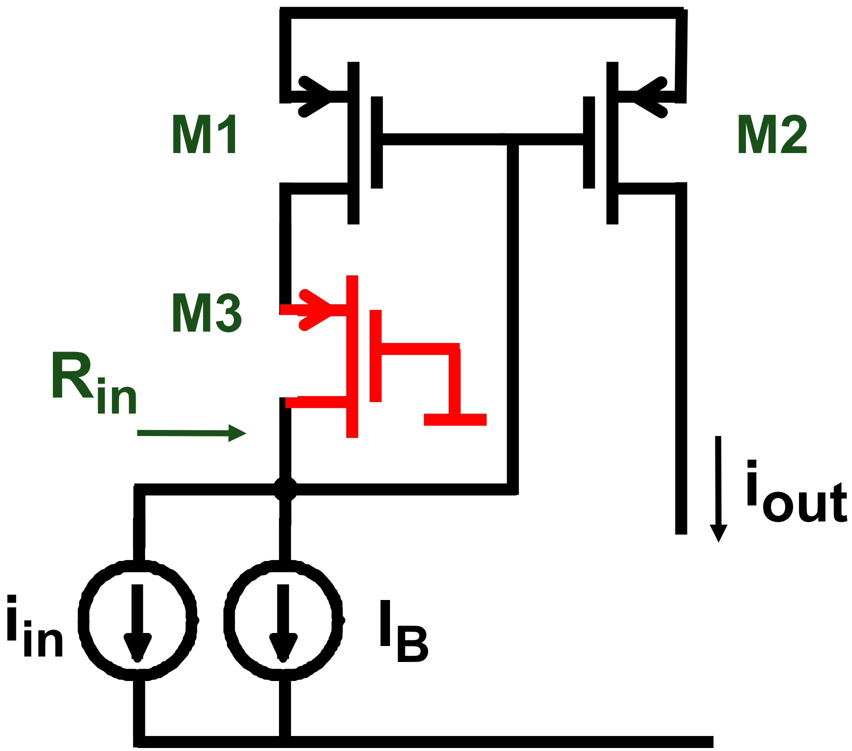
Current differential amplifier

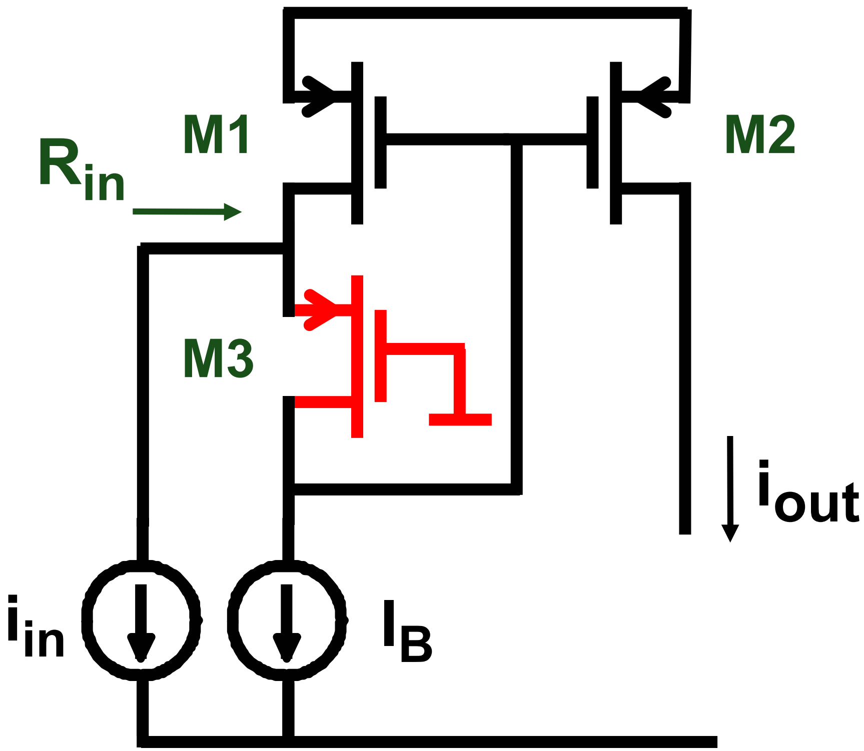


$i_{out} = I_B + i_{in}$ $\quad R_{in} = \frac{1}{g_{m1}}$

Is the same !

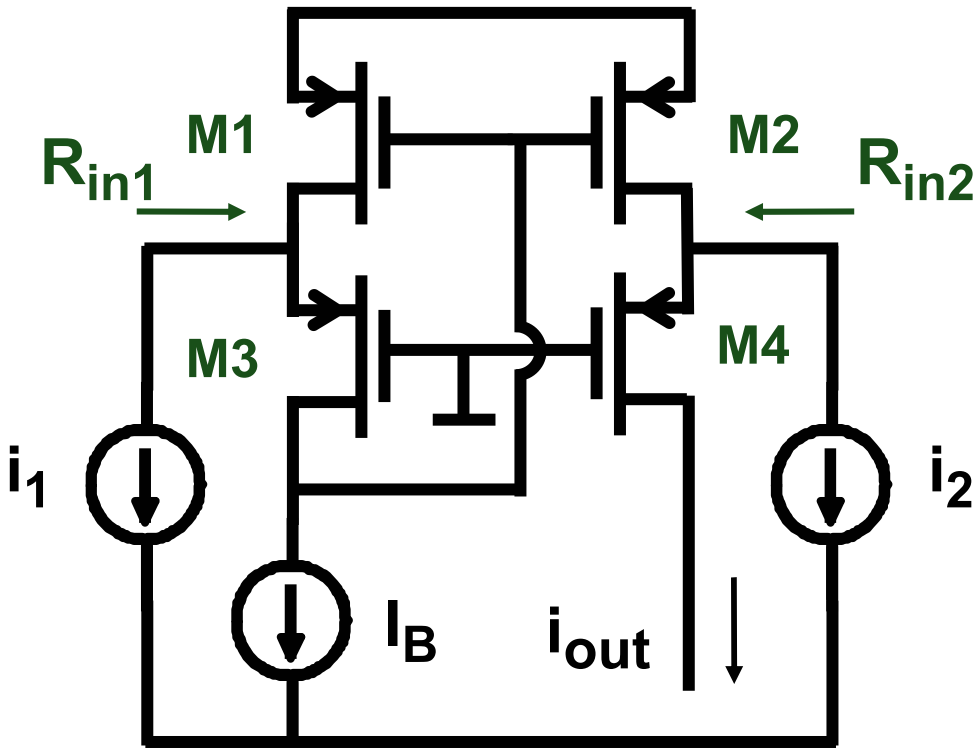
Current differential amplifier





$i_{out} = I_B + i_{in}$ $\quad R_{in} = \frac{1}{g_{m1}}$ $\qquad R_{in} = \frac{1}{g_{m1}} \frac{1}{g_{m3} r_{o3}}$

Current differential amplifier



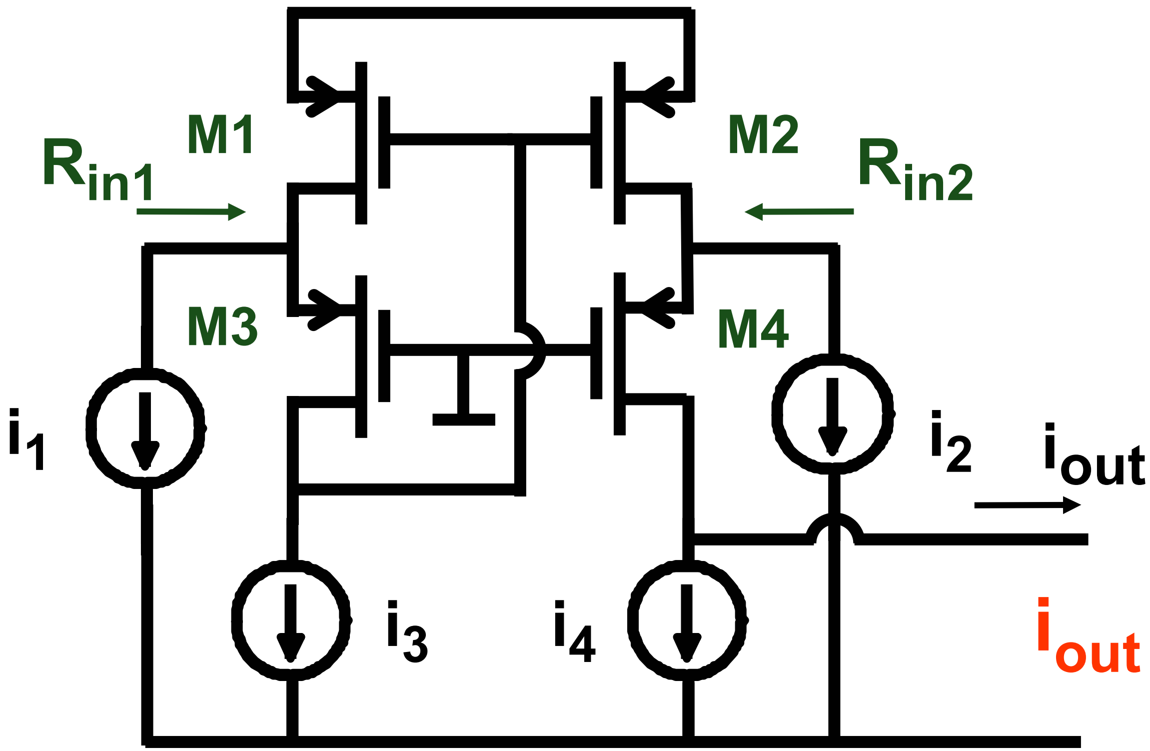
$$i_{out} = I_B + i_1 - i_2$$

$$R_{in1} = \frac{1}{g_{m1}} \frac{1}{g_{m3} r_{o3}}$$

$$R_{in2} = \frac{1}{g_{m4}}$$

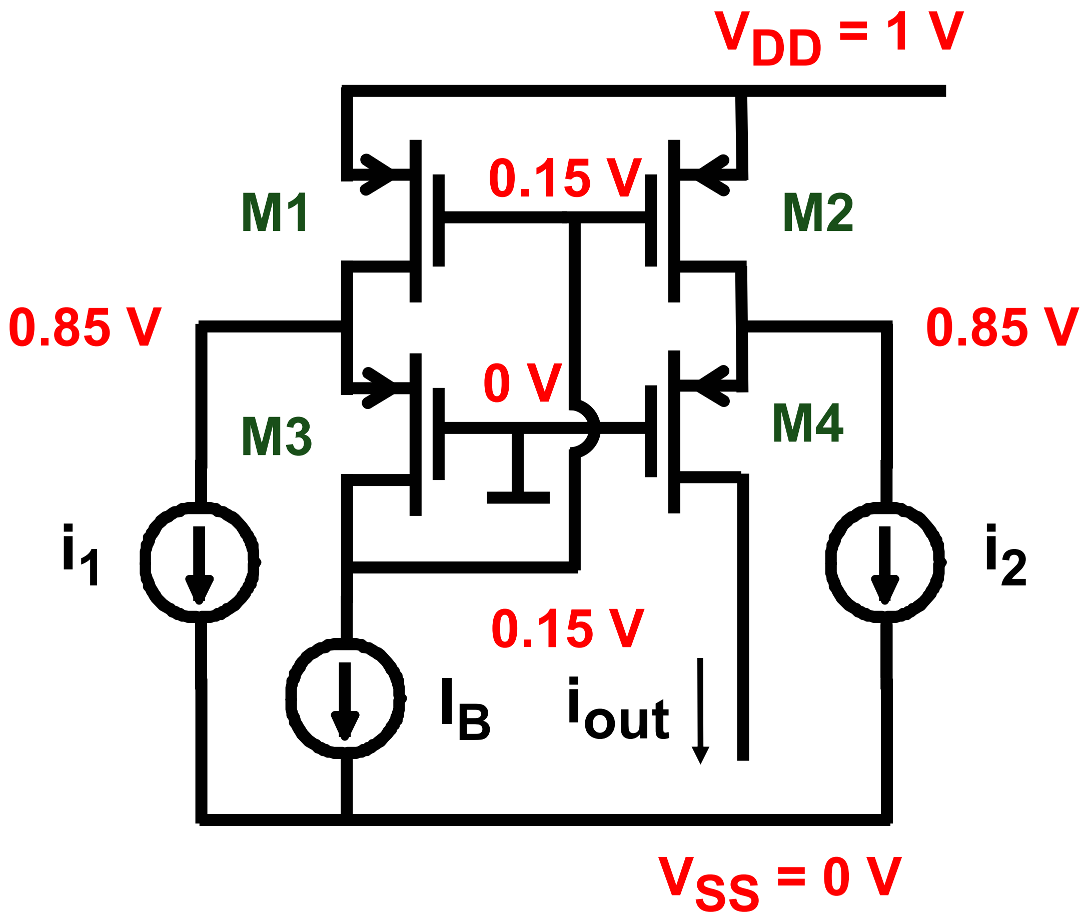
Ref. Fischer, JSSC June 87, 330-340

4-input current amplifier



$$i_{out} = i_1 - i_2 + i_3 - i_4$$

Low voltage operation



$i_{out} = I_B + i_1 - i_2$

$V_{GS} = 0.85$ V
$V_{DSsat} = 0.15$ V

$V_{outmax} = 0.7$ V

For $V_T = 0.7$ V
$V_{DDmin} \approx 0.6$ V
For $V_T = 0.3$ V
$V_{DDmin} \approx 0.6$ V

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