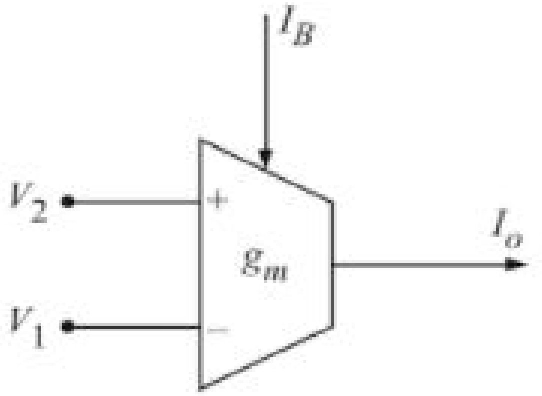
Operational transconductance amplifier

- **Operational transconductance amplifier (OTA)** is a monolithic direct coupled differential voltage controlled current source. They have a differential input and an output that is single-ended.
- OTA are described by transconductance gain **gm** instead of voltage-gain. They are very suitable for a broad variety of applications because they are similar to op-amp.
- As opposed to the operational amplifier, OTA has an ability to change gain which provides greater flexibility in design of analog circuits. The transconductance of an OTA can be linearly controlled by changing bias current (Ib) or voltage (Vb) through an extra control terminal.



Operational transconductance amplifier

Differences between OTA and operational amplifier:

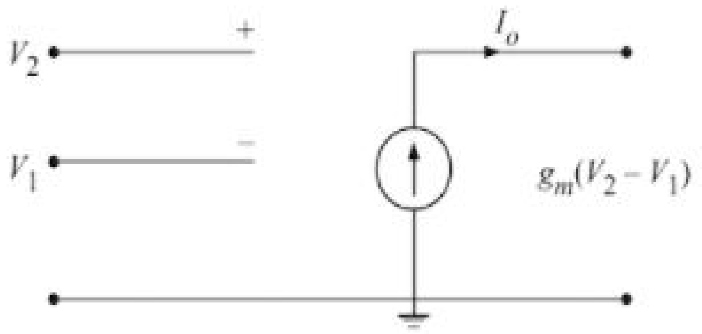
- OTA has an adjustable gain in contrast to the OP-amp. Network equations of the OTA circuits contain besides the values of passive elements, transconductance gm as an additional unknown.

- The output impedance of an OTA is very high in contrast to the operational amplifier. Consequently, OTA behaves as a current source at the output.

- As opposed to the linear OP-amp circuits, linear OTA circuits does not necessary use external negative feedback

Operational transconductance amplifier

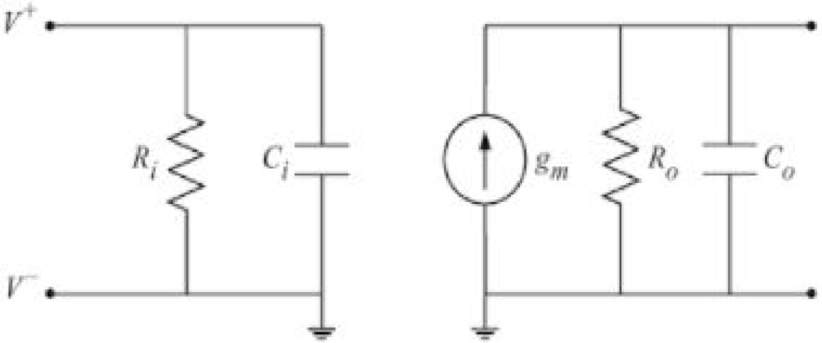
- **Characteristics of an ideal OTA**
  - Infinite input resistance $R_{in} \rightarrow \infty$
  - Infinite output resistance $R_o \rightarrow \infty$
  - Infinite frequency bandwidth $\omega_0 \rightarrow \infty$
  - The amplifier is ideally balanced: $I_0=0$ when $V_1=V_2$
  - Transconductance gm is finite and controllable with the bias current IB



Operational transconductance amplifier

- **Characteristics of a real OTA**
  - Finite input resistance R_{in}
  - Finite output resistance R_O
  - Offset voltage
  - Amplifies common mode signal
  - Finite bandwidth

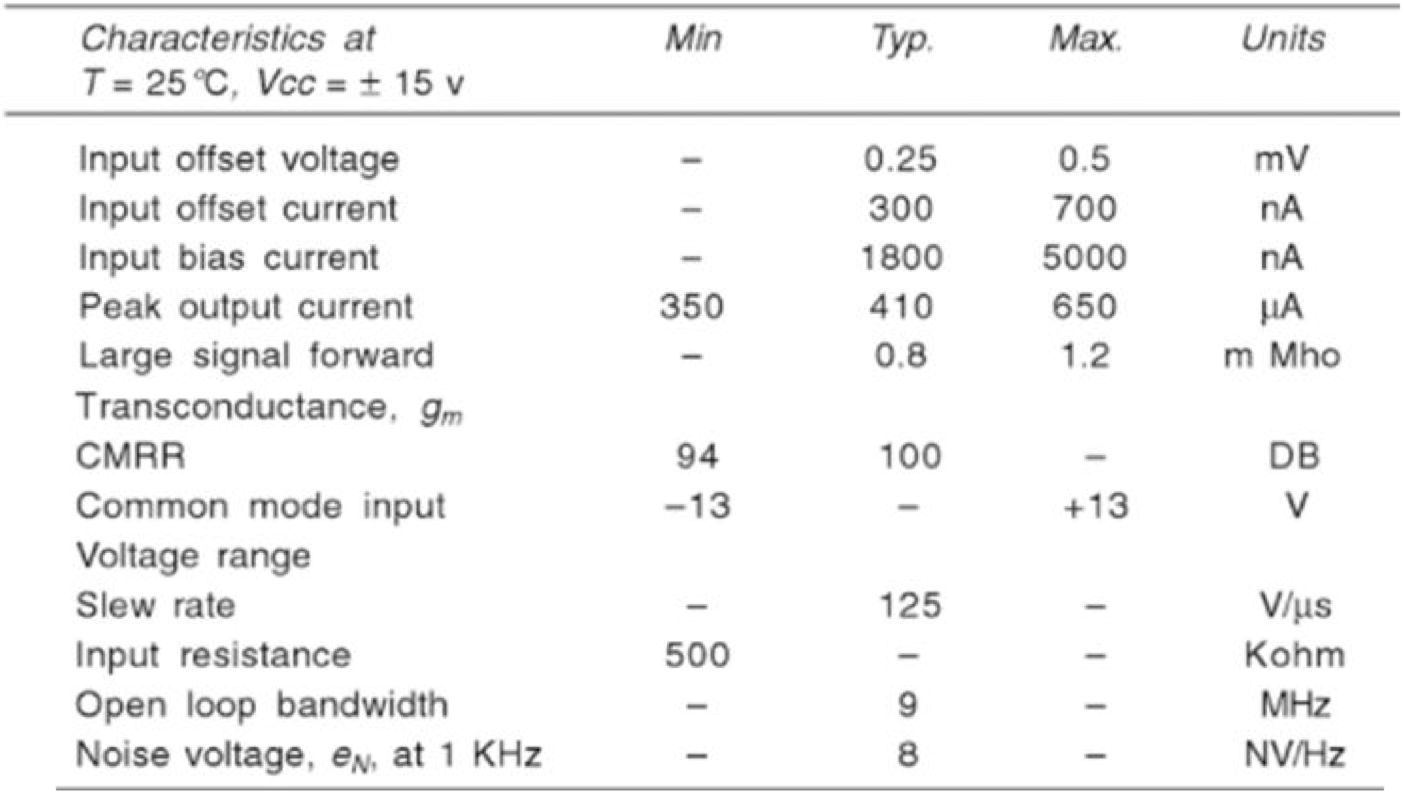
$$g_m(s) = \frac{g_{m0} \cdot \omega_a}{s + \omega_a}$$



Open loop transconductance is constant at lower frequencies. and monotonically decrease after a roll off frequency ω_a.

Operational transconductance amplifier

- **Characteristics of a real OTA**



Characteristics at *T = 25 °C, Vcc = ± 15 v*	*Min*	*Typ.*	*Max.*	*Units*
Input offset voltage	–	0.25	0.5	mV
Input offset current	–	300	700	nA
Input bias current	–	1800	5000	nA
Peak output current	350	410	650	μA
Large signal forward Transconductance, g_m	–	0.8	1.2	m Mho
CMRR	94	100	–	DB
Common mode input Voltage range	−13	–	+13	V
Slew rate	–	125	–	V/μs
Input resistance	500	–	–	Kohm
Open loop bandwidth	–	9	–	MHz
Noise voltage, e_N, at 1 KHz	–	8	–	NV/Hz

Operational transconductance amplifier

- Bipolar OTA
  - Single device: LM3080, CA3080
  - Dual OTA on a chip: LM13600, CA3280
  - Triple OTA on a chip: CA3060
  - Improved OTA with buffers and linearizing diods: LM13600, LM13700. Diodes are used to extend the dynamic range of the device. Buffers are used as an additional stage for the realization of a differential voltage controlled voltage source.

Operational transconductance amplifier

The current mirrors

The current mirrors are subcircuits particularly useful for the distribution of bias currents in larger circuits.

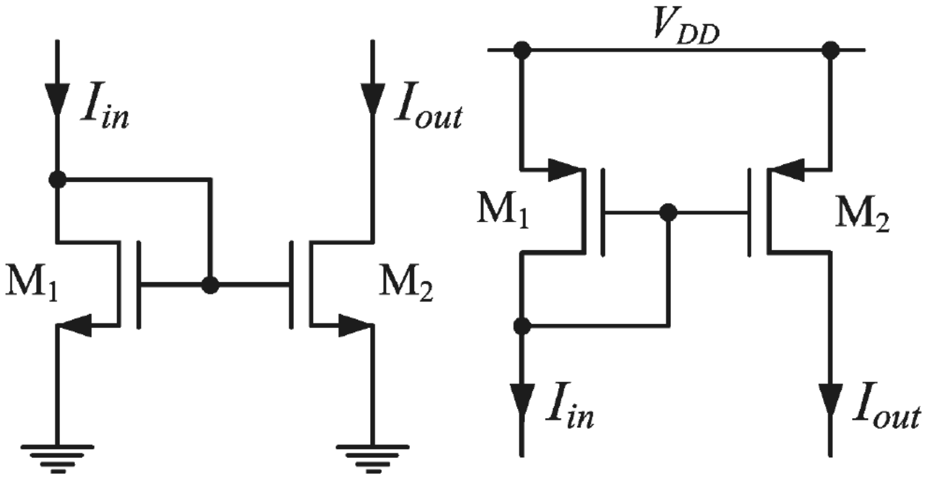
The performance requirements for current mirrors are similar as for current sources:

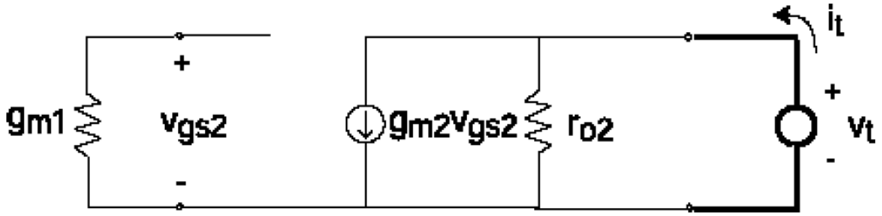
- The output resistance must be as large as possible in order to reduce the dependence of the output;
- The input resistance must be as small as possible;
- The minimum allowed output voltage and minimum input voltage must be as small as possible;
- The current gain must be precisely defined, constant with the supply voltage and temperature.

Operational transconductance amplifier

The simple MOS current mirror

- The simple current mirror can be obtained by using a transistor in diode connection M1 (its drain is shorted to its gate) and an output transistor in common source configuration, M2. The gate source voltage of the both transistors is set by the injected input or reference current, I_{in}.



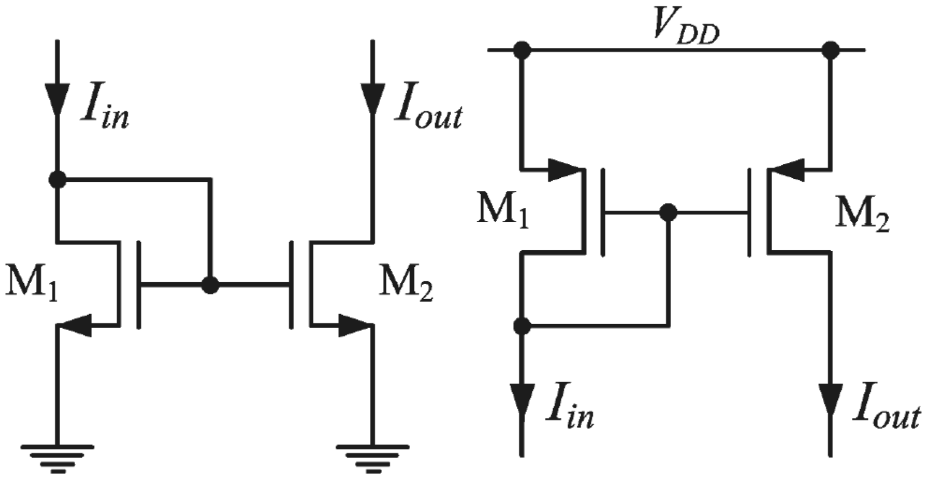


$$r_{out} = \frac{v_t}{i_t} = r_{02}$$

Operational transconductance amplifier

The simple MOS current mirror

- Under assumption that both transistor operate in saturation mode we can determine the relationship between reference current and output current. The output current I_{out} is related to the reference current I_{ref} by the ratio of the aspect ratios of the transistors.



$$I_{D1} = \frac{1}{2} \cdot k_n' \left(\frac{W}{L}\right)_1 (V_{GS} - V_{tn})^2$$

$$I_{D2} = \frac{1}{2} \cdot k_n' \left(\frac{W}{L}\right)_2 (V_{GS} - V_{tn})^2$$

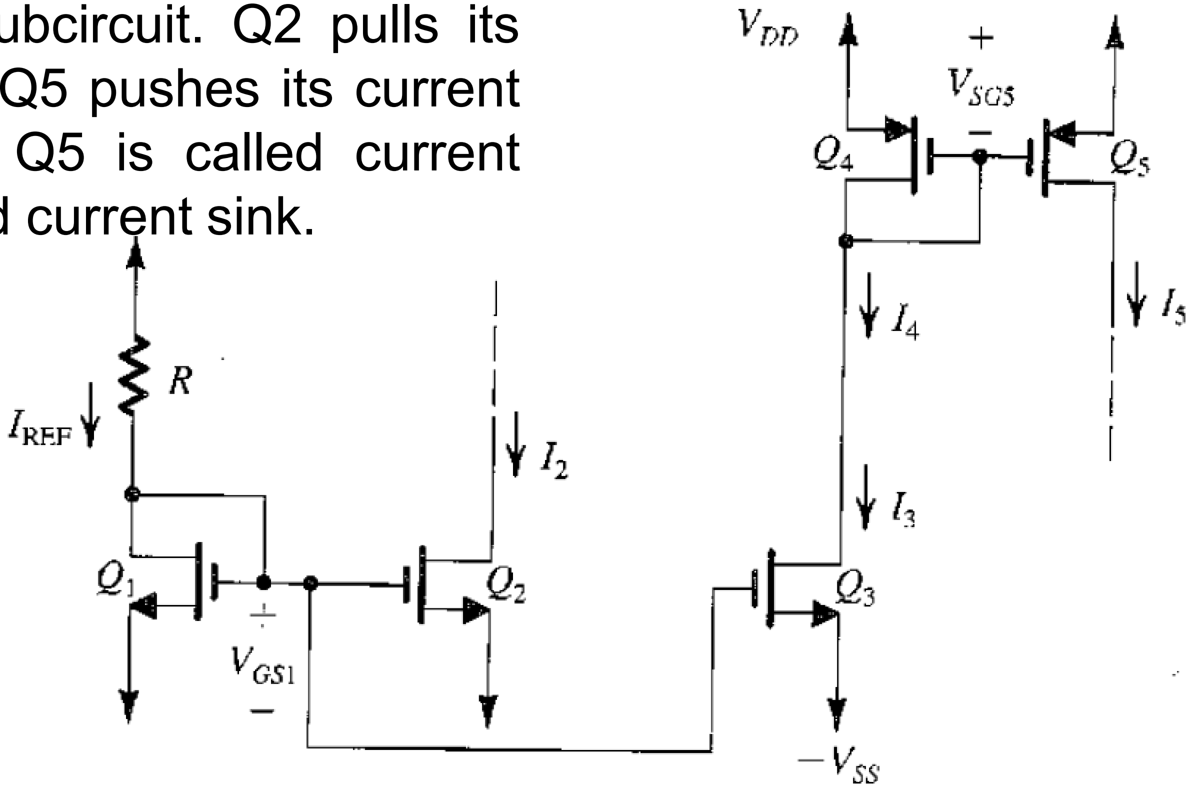
$$I_{D1} = I_{REF} = \frac{V_{DD} - V_{GS}}{R}$$

$$I_{D1} = \frac{I_0}{I_{REF}} = \frac{(W/L)_1}{(W/L)_2}$$

Operational transconductance amplifier

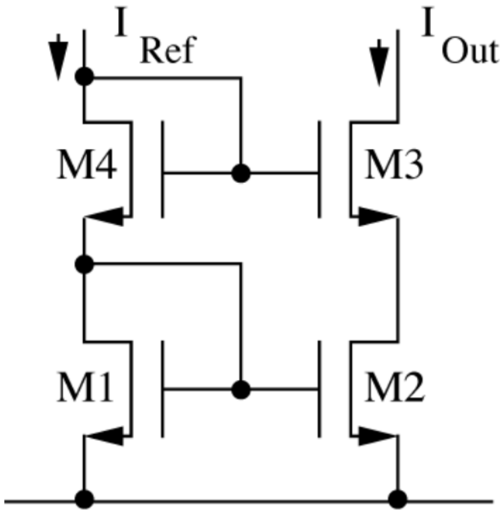
A current steering circuit

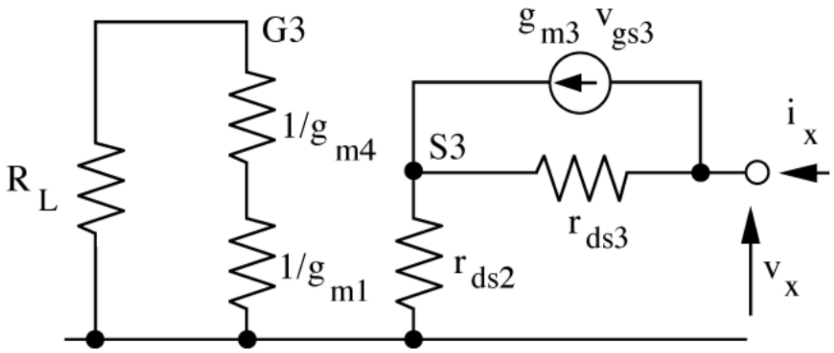
Once a constant current is generated it can be replicated to provide DC bias currents for the various stages. This function realized by the current steering subcircuit. Q2 pulls its current from load and Q5 pushes its current I5 into a load. Thus, Q5 is called current source and Q2 is called current sink.



Operational transconductance amplifier

Cascode current mirror





The cascode configuration is used to increase the output resistance of the current sink/source.

$$v_x = r_{DS2} \cdot i_x + r_{DS3} \cdot \left(i_x - g_{m3} \cdot v_{GS3}\right)$$

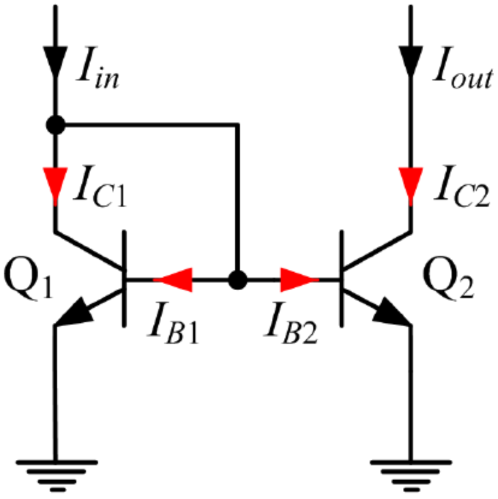
$$v_{GS3} = -v_{S3} = -r_{DS2} \cdot i_x$$

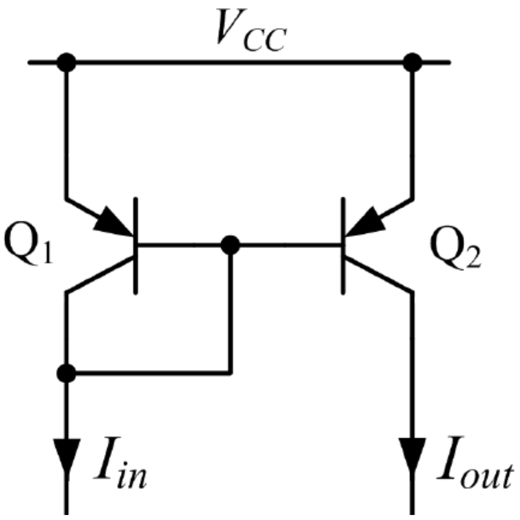
$$r_{out} = \frac{v_x}{i_x} = r_{DS2} + r_{DS3} + g_{m3} \cdot r_{DS3} \cdot r_{DS2} \approx g_{m3} \cdot r_{DS3} \cdot r_{DS2}$$

Operational transconductance amplifier

- **The simple bipolar current mirror**

The current that flows through the diode connected transistor Q1 establishes a base-emitter voltage. This voltage is than applied between base and emitter of Q2. If both transistor have the same emitter-base junction area then the collector current of Q2 will be equal to that of Q1.





$$I_C = I_S \cdot e^{\frac{V_{BE}}{V_T}}$$

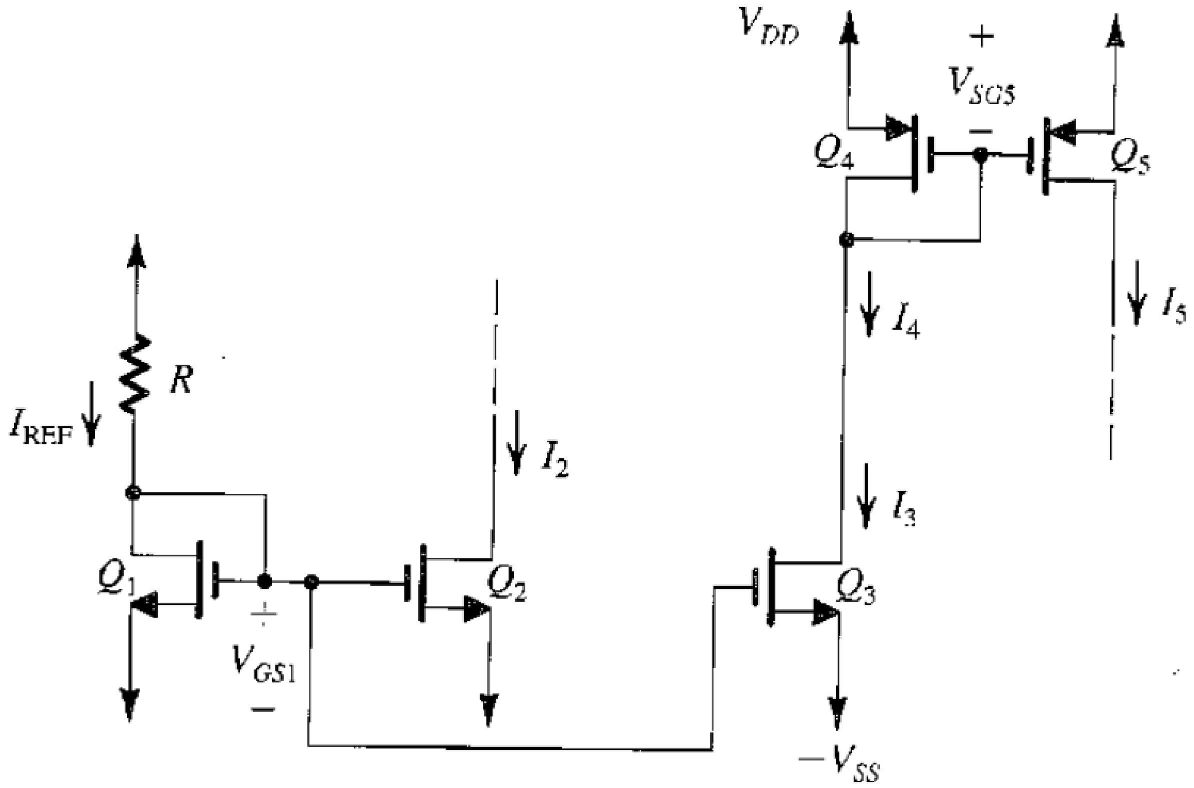
$$\frac{I_{C1}}{I_{C2}} = \frac{I_{S1}}{I_{S2}}$$

$$\frac{I_0}{I_{REF}} = \frac{\mathit{Area\ of}\ \text{BEJ}\ \mathit{of}\ Q2}{\mathit{Area\ of}\ \text{BEJ}\ \mathit{of}\ Q1}$$

Operational transconductance amplifier

Problem 6.1

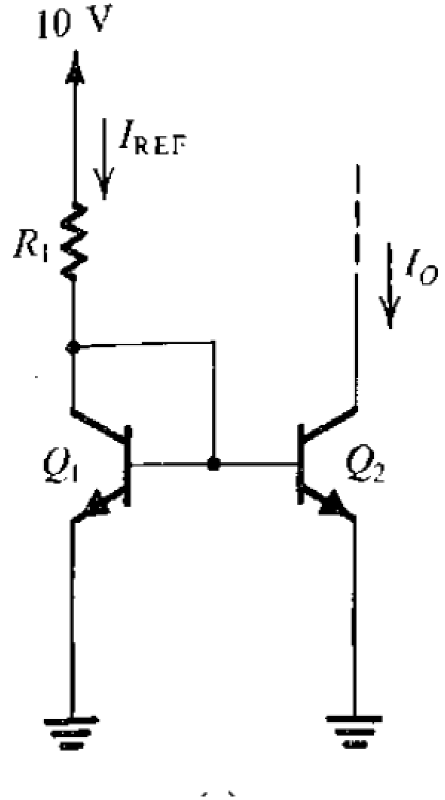
For the circuit shown in figure, let V_{DD}= Vss = 15 V, V_{tn}= 0.6 V, V_{tp} = -0.6 V, all channel lengths L=1 μV, k_n’ = 200 $\mu A/V^2$, k_p' = 80 $\mu A/V^2$, and λ = 0. For I_{REF} =100 μA, find the widths of all transistors to obtain I2 = 60 μA, I3 = 20 μA and I5 = 80 μA. The minimum voltaga at the drain of Q2 is V_{SS}+0.2 V and the maximal voltage at the drain of Q5 is V_{DD}-0.2V.



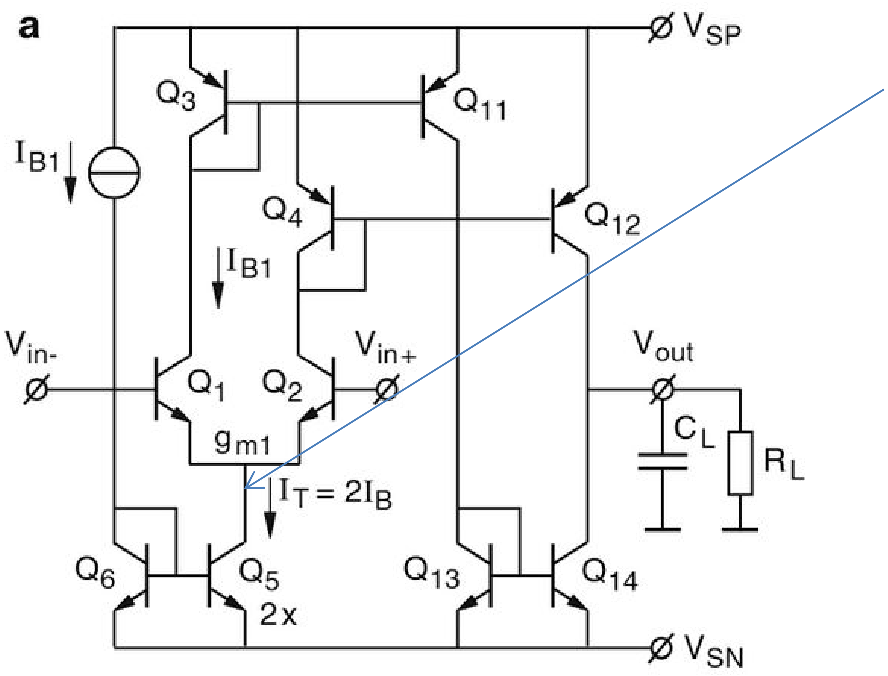
Operational transconductance amplifier

Problem 6.2

For the basic current-source circuit shown in figure determine the value of R for generating current of 10 μA. Assume that V_{BE} *is 0.7 V* at a current of 1 mA and neglect the effect of finite β.



Operational transconductance amplifier



Differential pair: Q1, Q2

$$I_T = I_{E1} + I_{E2}$$

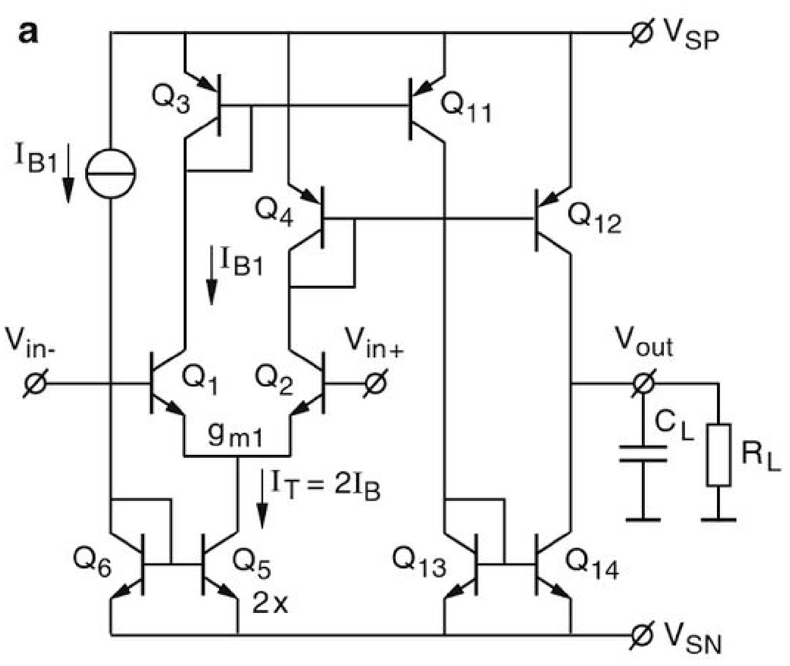
$$I_{E1} \approx I_{C1} = I_S \cdot \exp(V_{BE1} / V_T)$$

$$I_{E2} \approx I_{C2} = I_S \cdot \exp(V_{BE2} / V_T)$$

$$I_{E1} = \frac{I_T}{1 + \dfrac{I_{E2}}{I_{E1}}} = \frac{I_T}{1 + \exp\left(\dfrac{V_{BE2} - V_{BE1}}{V_T}\right)}$$

$$I_{E2} = \frac{I_T}{1 + \dfrac{I_{E1}}{I_{E2}}} = \frac{I_T}{1 + \exp\left(\dfrac{V_{BE1} - V_{BE2}}{V_T}\right)}$$

Operational transconductance amplifier

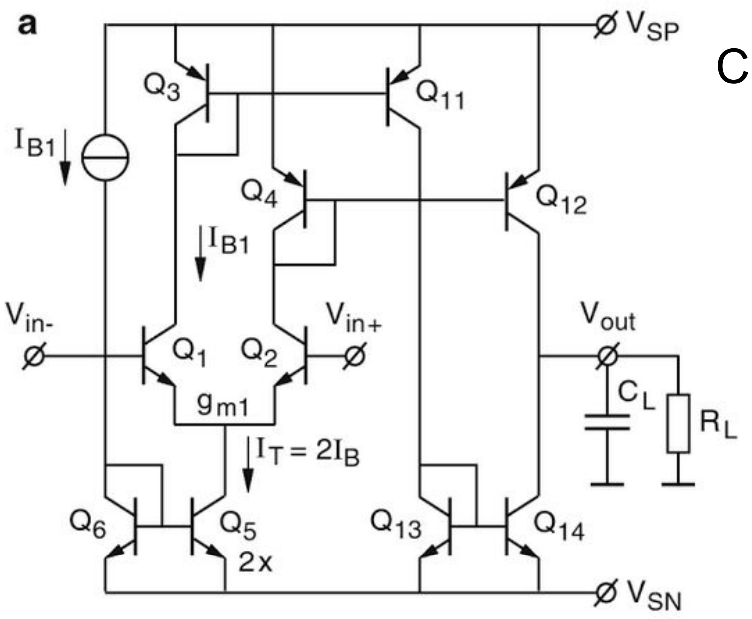


$$x = \frac{V_{BE2} - V_{BE1}}{V_T} = \frac{V_{in}}{V_T}$$

$$I_{E1} = \frac{I_T}{1 + e^{-x}} \cdot \frac{e^{\left({}^{x}\!/_{2}\right)}}{e^{\left({}^{x}\!/_{2}\right)}} = I_T \frac{e^{\left({}^{x}\!/_{2}\right)}}{e^{\left({}^{x}\!/_{2}\right)} + e^{-\left({}^{x}\!/_{2}\right)}}$$

$$I_{E2} = \frac{I_T}{1 + e^{x}} \cdot \frac{e^{-\left({}^{x}\!/_{2}\right)}}{e^{-\left({}^{x}\!/_{2}\right)}} = I_T \frac{e^{-\left({}^{x}\!/_{2}\right)}}{e^{-\left({}^{x}\!/_{2}\right)} + e^{\left({}^{x}\!/_{2}\right)}}$$

Operational transconductance amplifier



Current mirrors:(Q3,Q11),(Q5,Q6),(Q4,Q12),(Q13,Q14)

$$I_{C1} = I_{C11} = I_{C14}$$

$$I_{C2} = I_{C12}$$

$$I_{out} = I_{C14} - I_{C12} = I_{C1} - I_{C2}$$

$$I_o = I_{C1} - I_{C2} = I_T \frac{e^{\left(x/2\right)} - e^{-\left(x/2\right)}}{e^{\left(x/2\right)} + e^{-\left(x/2\right)}}$$

$$I_o = I_T \cdot \tanh\left(\frac{x}{2}\right) = I_T \cdot \tanh\left(\frac{V_{in}}{2 \cdot V_T}\right)$$

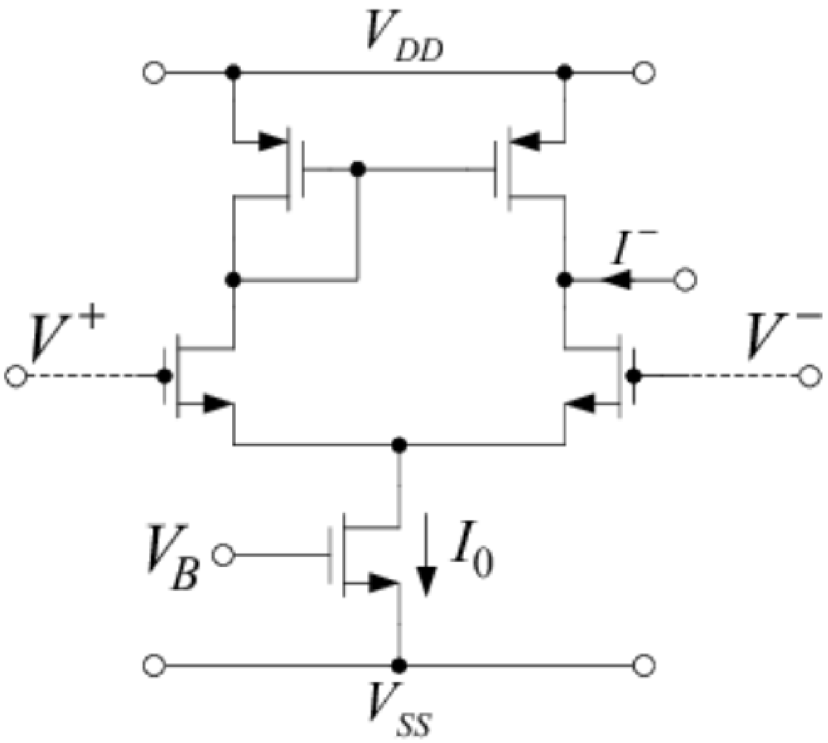
$$gm = \frac{dI_0}{dV_{in}} = \frac{I_T}{2 \cdot V_T} \cdot \sec h^2\left(\frac{V_{in}}{2 \cdot V_T}\right)$$

$$g_m = \frac{dI_0}{dV_{in}} \approx \frac{I_T}{2 \cdot V_T} \approx 19.2 \cdot I_T[A]$$

$$g_m = g_m(Q_1) = g_m(Q_2) = \frac{dI_{C1}}{dV_{BE1}}$$

Operational transconductance amplifier

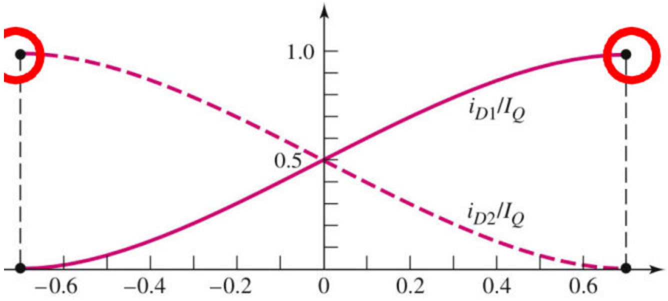
Onestage OTA (Milerov OTA)



$$i_{D1} = k_n\left(v_{GS1} - v_{tn}\right)^2$$

$$i_{D2} = k_n\left(v_{GS2} - v_{tn}\right)^2$$

$$i_{D1} + i_{D2} = I_0$$



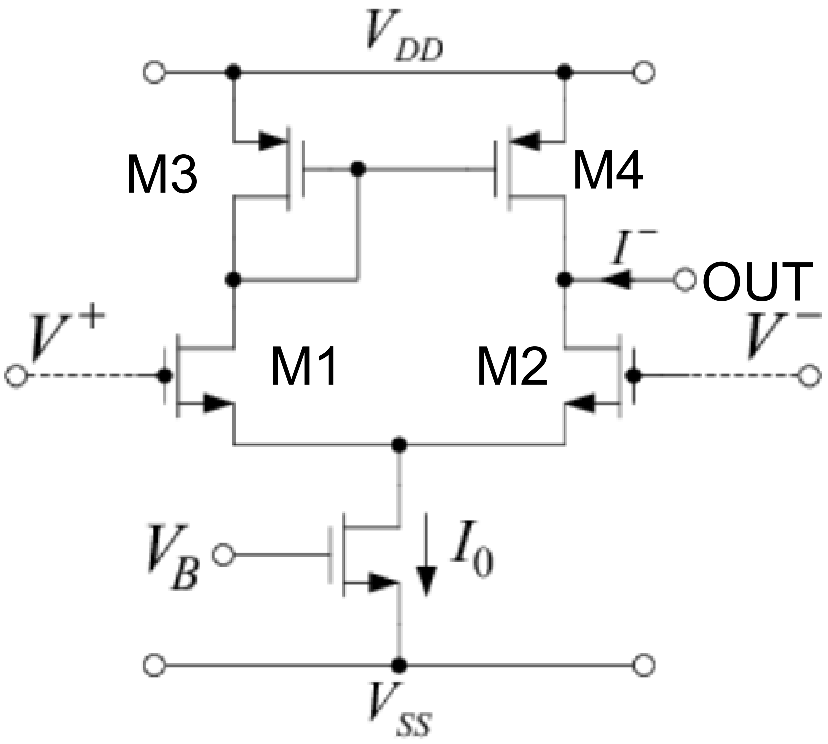
DC transfer characteristic for MOSFET differential pair

Transconductance is the slope of the DC transfer characteristic. Maximum of *gm* occurs at v_d=0:

$$g_m(\max) = \left.\frac{di_{D1}}{dv_d}\right|_{v_d = 0} = \sqrt{\frac{k_n I_0}{2}} = \frac{g_m}{2}$$

Operational transconductance amplifier

Onestage OTA (Milerov OTA)

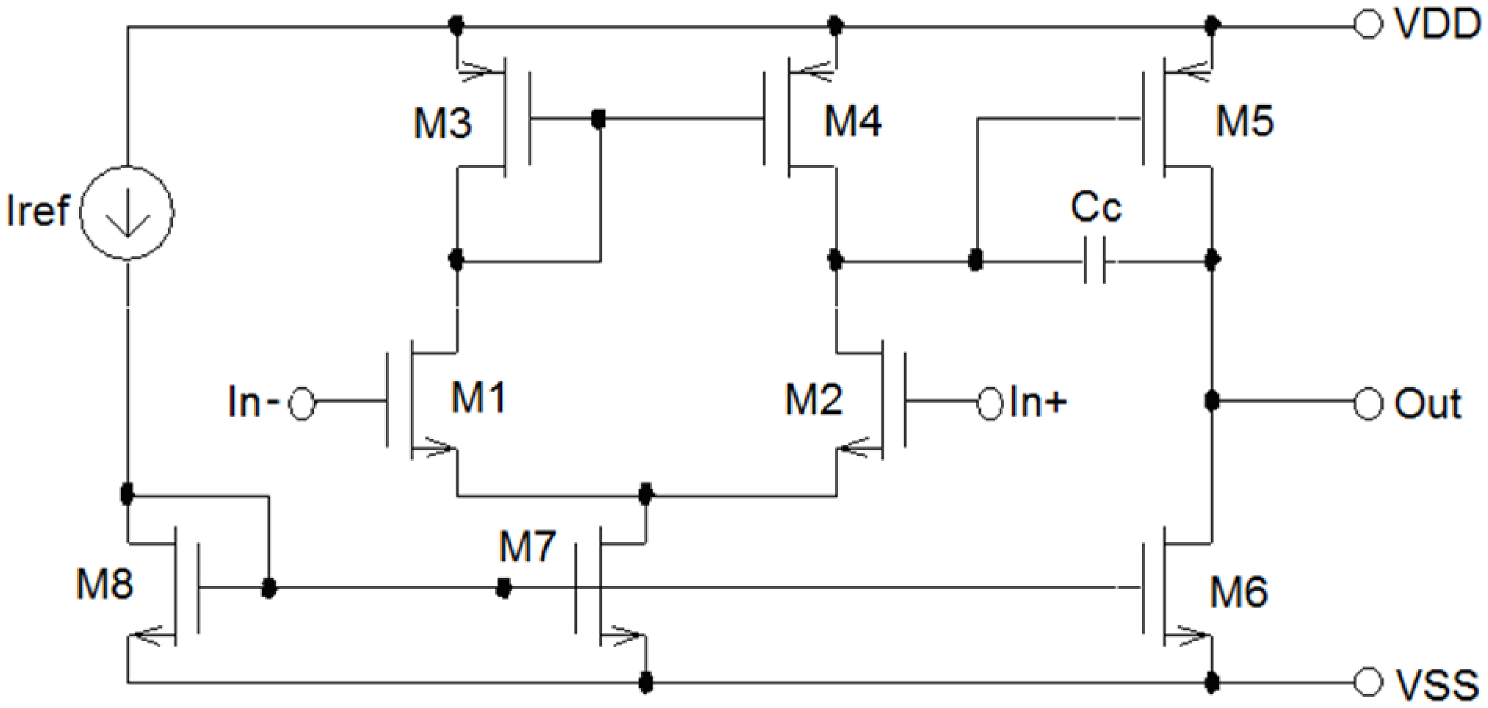


Rules for transistor sizing:

- M1 and M2 choose large W for high gain
- M3 and M4 choose large L for high gain and low offset

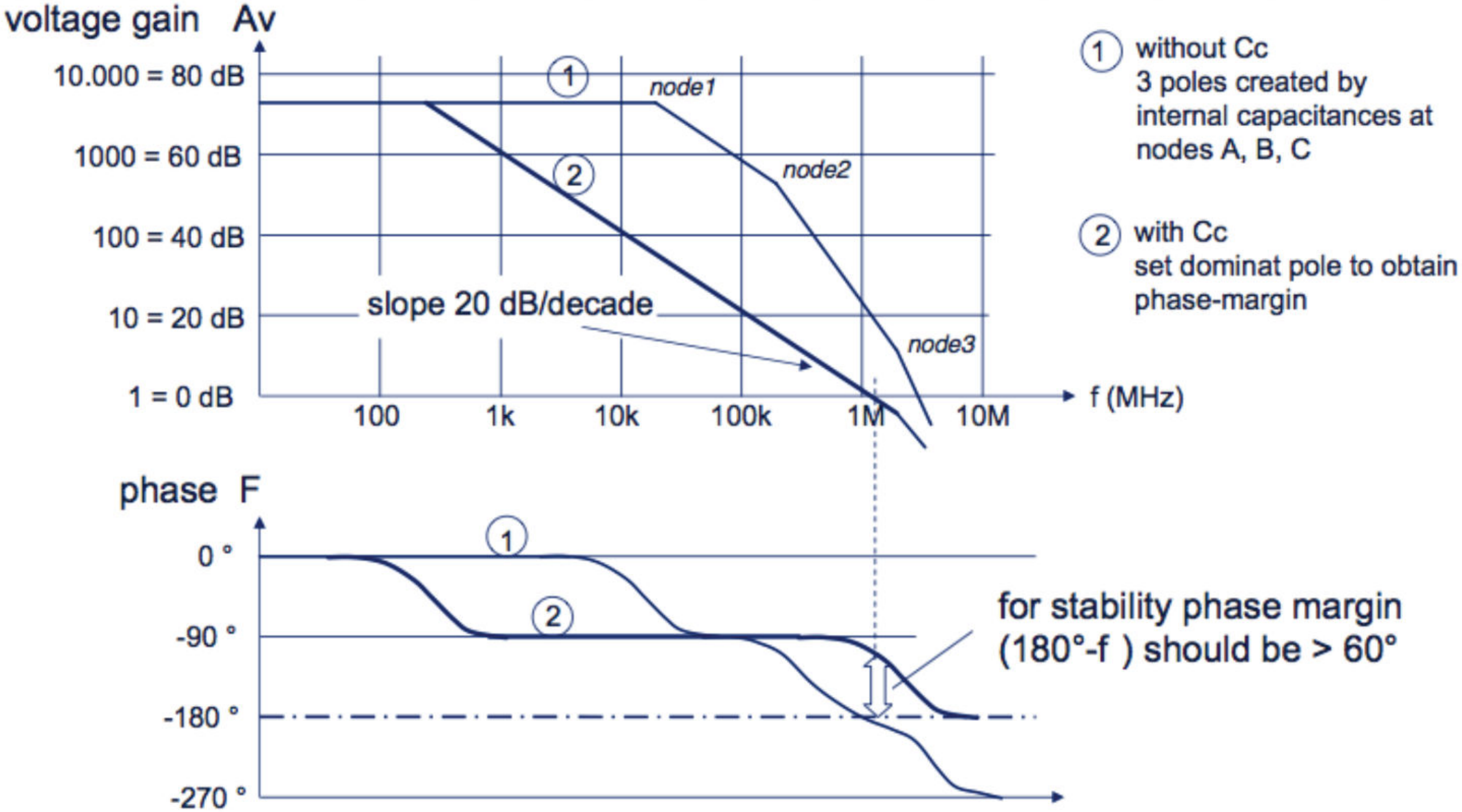
Operational transconductance amplifier

Twostage OTA (Miler OTA)



In order to use 2-stage OTA in a circuit with feedback it is necessary to add a compensation capacitor C_C or compensation network R+C

Operational transconductance amplifier



① without Cc
3 poles created by
internal capacitances at
nodes A, B, C

② with Cc
set dominat pole to obtain
phase-margin

for stability phase margin
(180°-f) should be > 60°

Operational transconductance amplifier

Onestage OTA (Milerov OTA)

Bipolar: gm increases linear with current

$$I_C = I_S \cdot e^{\frac{V_{BE}}{Vt}}$$

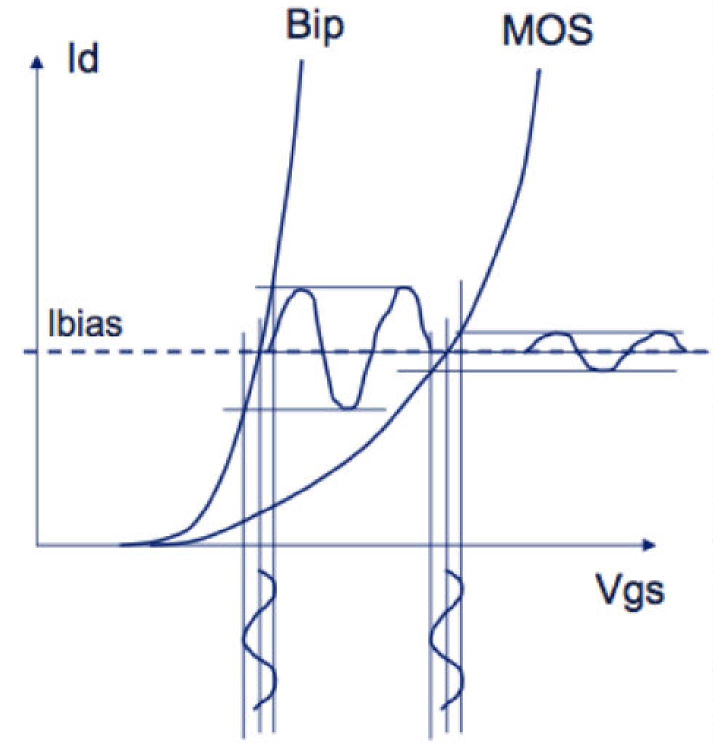
$$g_m = \frac{d\ Ic}{d\ Vbe} = \frac{I_C}{Vt}$$

MOS: gm increases with squareroot of current

$$Id = k \cdot \frac{w}{l} \cdot (Vgs - Vth)^2$$

$$g_m = \frac{d\ Id}{d\ Vbe} = k \cdot \frac{w}{l} \cdot 2 \cdot (Vgs - Vth)$$

$$g_m = 2 \cdot \sqrt{k \cdot \frac{w}{l} \cdot Id}$$



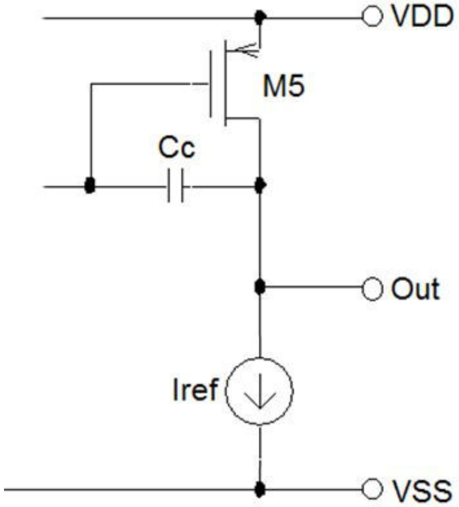
bipolar transistor will achive more gm

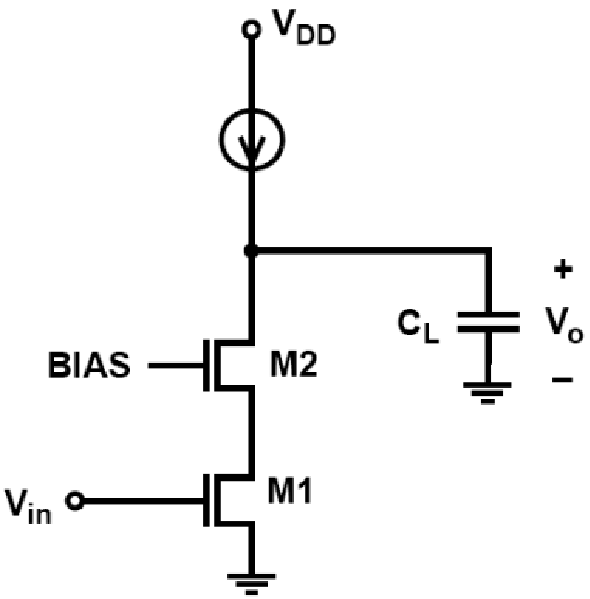
Operational transconductance amplifier

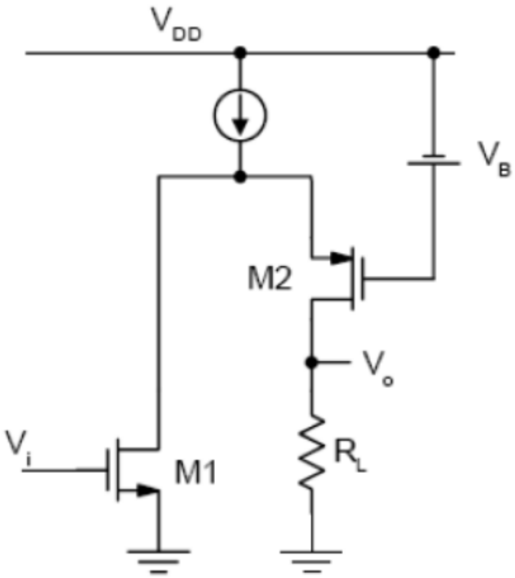
Outpu stage of an OTA

- **Common source amplifier**
- **Cascode amplifier** has a high output resistance and high gain $R_0 \approx r_{01} \cdot r_{01} \cdot g_{m2}$

- **Folded cascode amplifier** has an identical topology as cascode amplifier with respect to the AC current. The advantage of this circuit is a larger dynamic range which is achieved by an additional voltage supply VB.

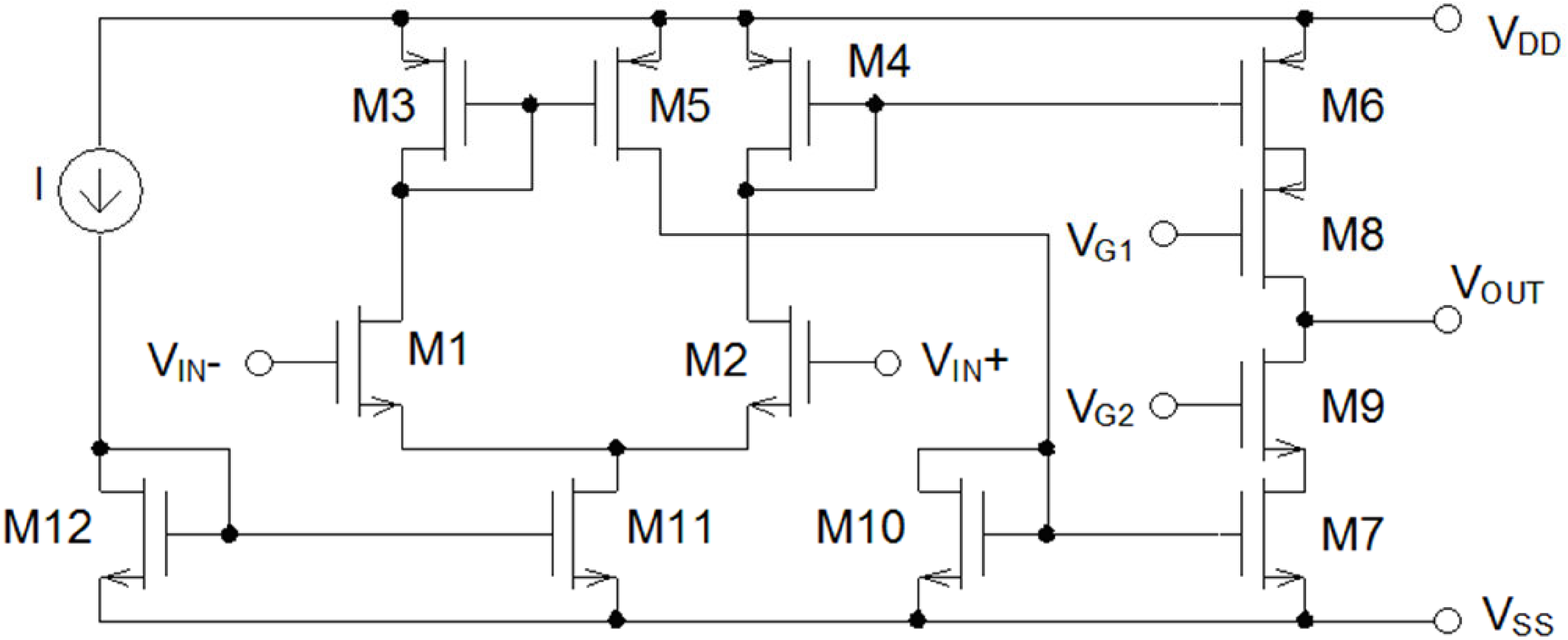






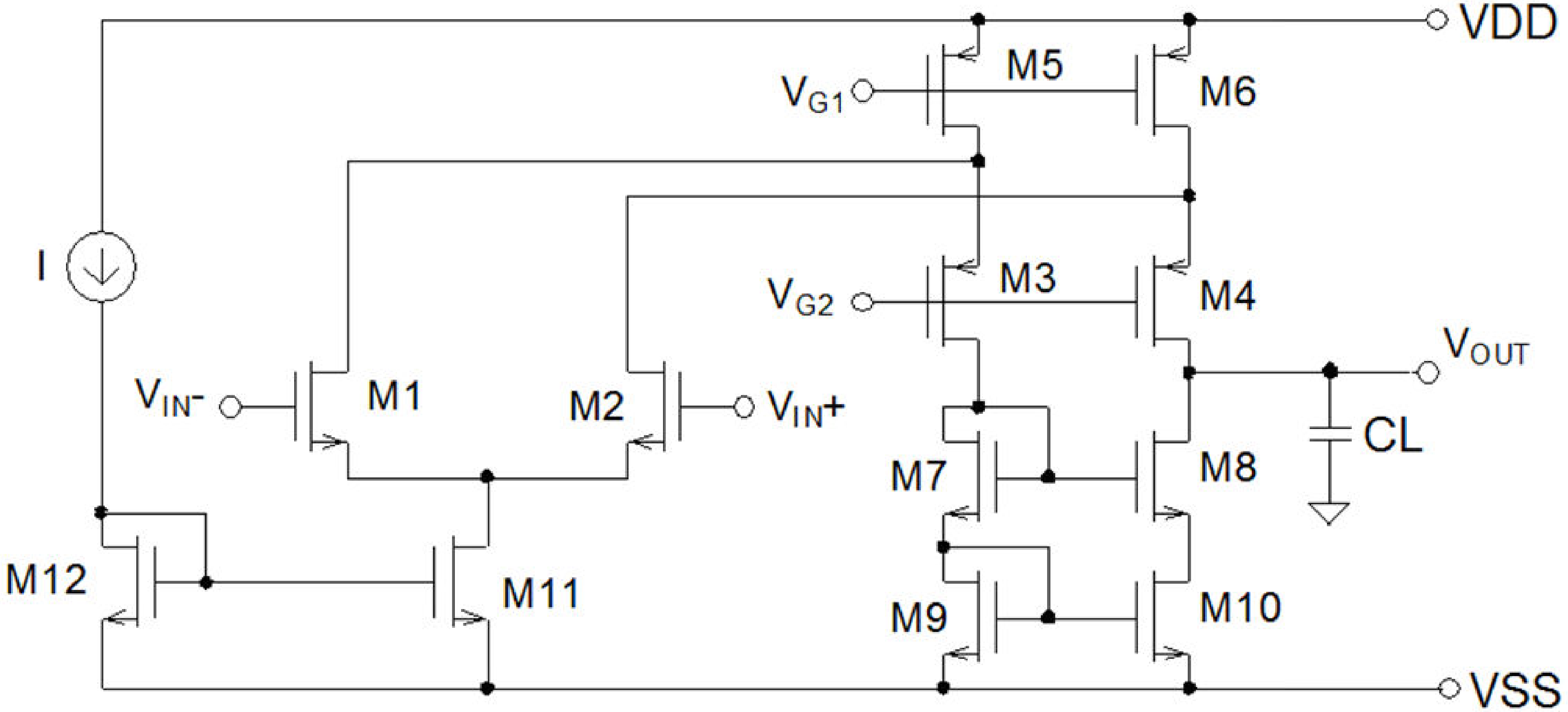
Operational transconductance amplifier

Cascode OTA



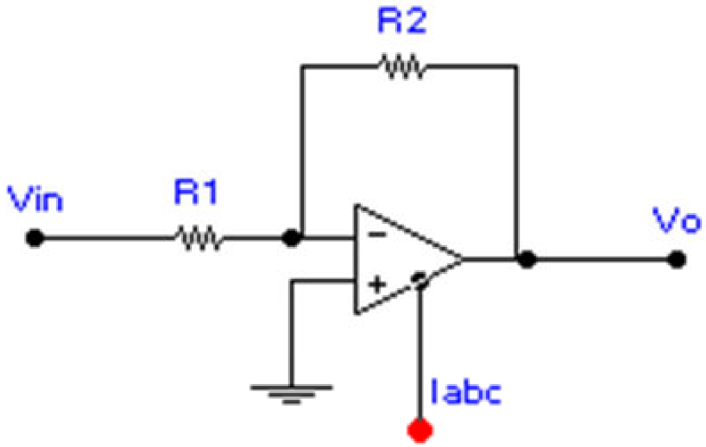
Operational transconductance amplifier

Foulded cascode OTA



Operational transconductance amplifier

An inverting amplifier realized with one OTA



$$\frac{V_0}{V_{in}} = \frac{1 - g_m \cdot R_2}{1 + g_m \cdot R_1}$$

$$R_0 = \frac{R_1 + R_2}{1 + g_m \cdot R_1}$$

In the case when gmR1>>1 follows:

$$\frac{V_0}{V_{in}} \approx -\frac{R_2}{R_1}$$

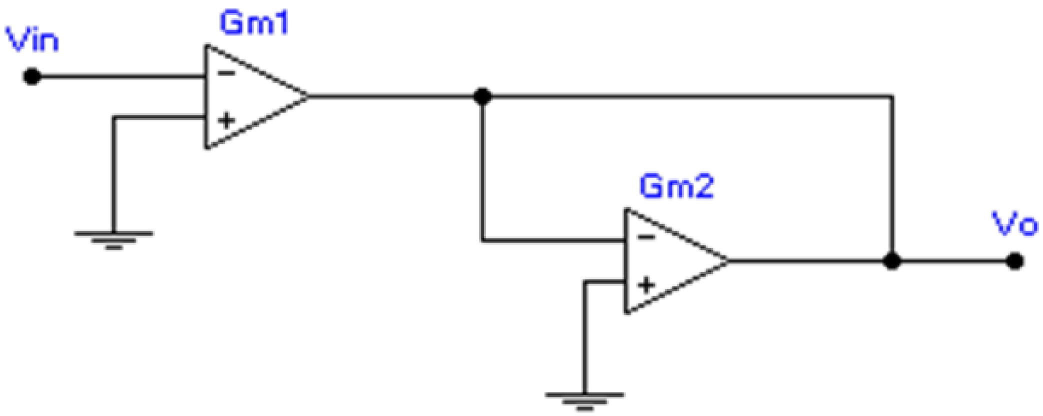
$$R_0 \approx \frac{R_1 + R_2}{g_m \cdot R_1}$$

Operational transconductance amplifier

Inverting amplifier realized with two OTAs

This circuit does not contain passive components. Voltage gain and output resistance can be adjusted with bias currents of the OTAs.

$$\frac{V_0}{V_{in}} = -\frac{g_{m1}}{g_{m2}}$$



$$R_0 = \frac{1}{g_{m2}}$$

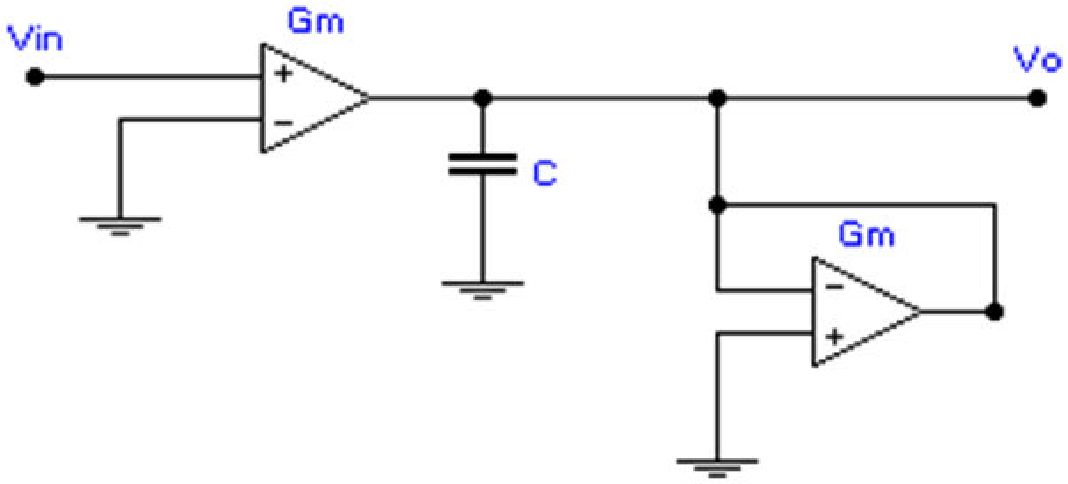
Operational transconductance amplifier

Active filter realized by OTA

- Many different active filter configurations can be realized by using OTA.

These filters have ability to adjust critical frequencies, gain or both these parameters at the same time.

- In a first order filter section OTA denoted as Gm2 is connected in such a way that it represents a resistor controlled by the voltage, R=1/gm2.



$$\frac{V_0}{V_{in}} = -\frac{g_{m1}}{g_{m2} + sC}$$

$$f_{3dB} = -\frac{g_{m2}}{2 \cdot \pi \cdot C}$$

Operational transconductance amplifier

6.3. Problem

The figure below shows a biquad filter section realized with two OTAs. Determine the types of the filter functions, corner frequency ω_o and Q-factor of the poles in the case when:

a) Vin =Va, Vb=Vc=0;

b) Vin =Vb, Va=Vc=0;

c) Vin =Vc, Va=Vb=0.