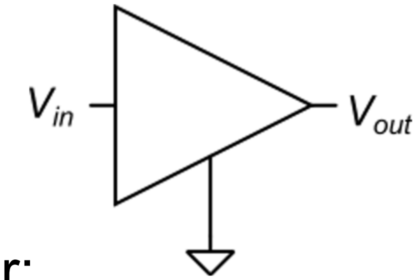
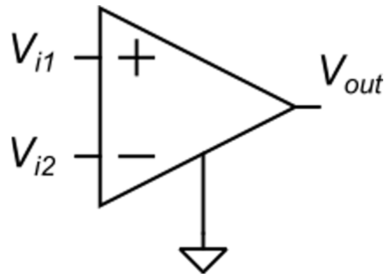
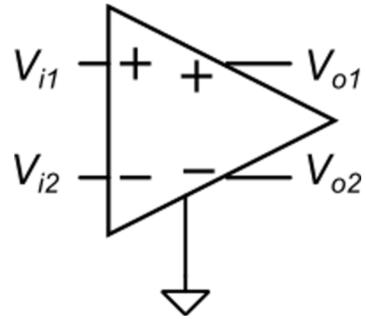
Voltage amplifiers: number of inputs and outputs



Unipolar:
single input
single output (single-ended, S/E)

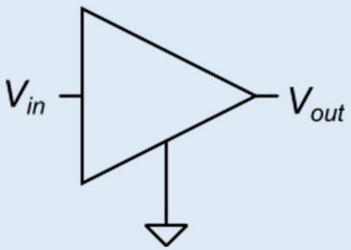


Differential:
differential input,
single output (single-ended, S/E)



Fully Differential:
differential input,
differential output

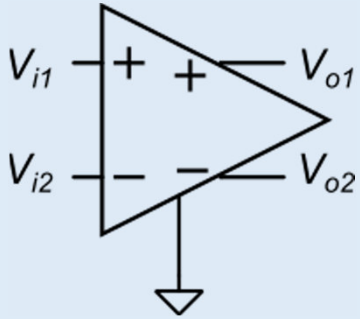
Voltage Amplifiers: gains



$$v_{out} = A_V v_{in}$$

$$v_{id} = v_{i1} - v_{i2}$$

$$v_{ic} = \frac{v_{i1} + v_{i2}}{2}$$



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

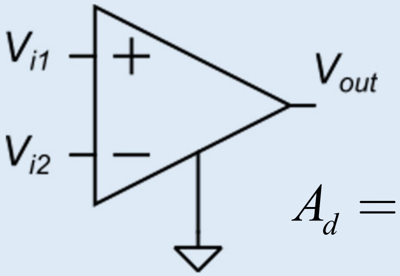
$$v_{oc} = \frac{v_{o1} + v_{o2}}{2}$$

$$A_{dd} = \left.\frac{v_{od}}{v_{id}}\right|_{v_{ic}=0}$$

$$A_{cd} = \left.\frac{v_{od}}{v_{ic}}\right|_{v_{id}=0}$$

$$A_{dc} = \left.\frac{v_{oc}}{v_{id}}\right|_{v_{ic}=0}$$

$$A_{cc} = \left.\frac{v_{oc}}{v_{ic}}\right|_{v_{id}=0}$$

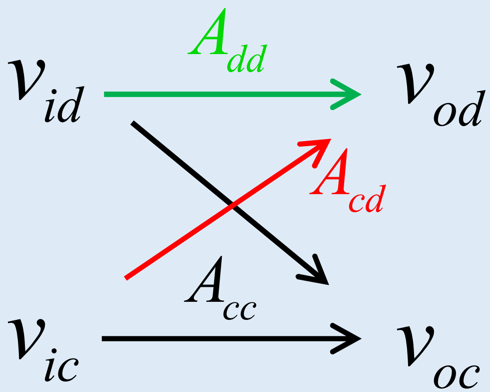


$$A_d = \left.\frac{v_{out}}{v_d}\right|_{v_c=0} \qquad A_c = \left.\frac{v_{out}}{v_c}\right|_{v_d=0}$$

$$v_d = v_{i1} - v_{i2}$$

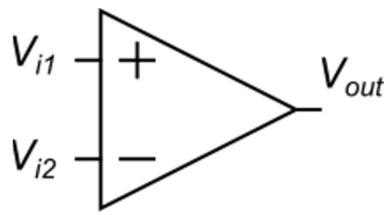
$$v_c = \frac{v_{i1} + v_{i2}}{2}$$

$$CMRR = \left|\frac{A_d}{A_c}\right|$$



$$CMRR = \left|\frac{A_{dd}}{A_{cd}}\right|$$

Differential amplifiers: parameters



$$V_{out} = A_d \left(V_{id} - V_{io} \right)$$

Linear response
(with input offset voltage)

Input voltage ranges:

Input differential range (maximum V_{ID} (V_D) to maintain an acceptable input-output linearity

$$-V_{DMAX} \le V_D \le V_{DMAX}$$

Input common-mode range: Interval of VC values where the amplifier behaves as designed

$$V_{CMIN} \le V_C \le V_{CMAX}$$

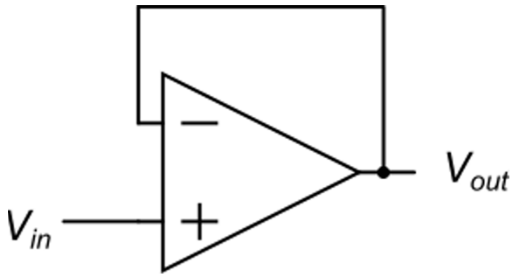
Output voltage range (Output voltage swing)

$$V_{OMIN} \le V_{out} \le V_{OMAX}$$

Outside the output range the amplifier stop working correctly (e.g. the output voltage tends to saturate)

Differential amplifiers: role of the input common mode range

Example: voltage follower (buffer amplifier)



In the ideal case:

$$V_{io} = 0, \;\; A_d \to \infty$$

We have:

$$V_C = V_{in}$$

$$V_D \cong 0$$

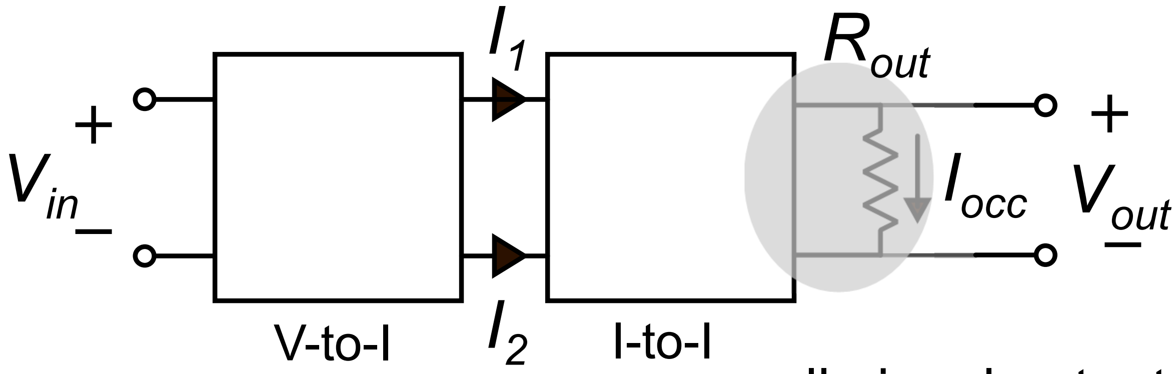
The voltage follower operates correctly only for V_{in} within the CM range

Another condition is clearly that V_{out} is within the output range

Then the conditions for correct operation are:

$$V_{out} = V_{in} \text{ only for } \begin{cases} V_{CMIN} \le V_{in} \le V_{CMAX} \\ V_{OMIN} \le V_{out} \le V_{OMAX} \end{cases}$$

Single Stage Voltage Amplifiers



The processed currents are finally conveyed to an output resistance (R_{out}) and converted back to a voltage (V_{out}). In most cases, Rout is not a physical resistor, but is the output differential resistance of the I-to-I network. For this reason, one of the function of the I-to-I network is increasing the output resistance to increase gain

The first component converts the input voltage (single or differential) into a current (single or differential)

example

$$I_1 - I_2 = G_{m1} V_{in}$$

small-signal output voltage

$$v_{out} = i_{occ} R_{out}$$

The second component is a current processing network, that takes the input currents and applies simple linear operations such as:

- Addition and subtraction
- Addition of constant currents
- Multiplication by a constant gain factor

example

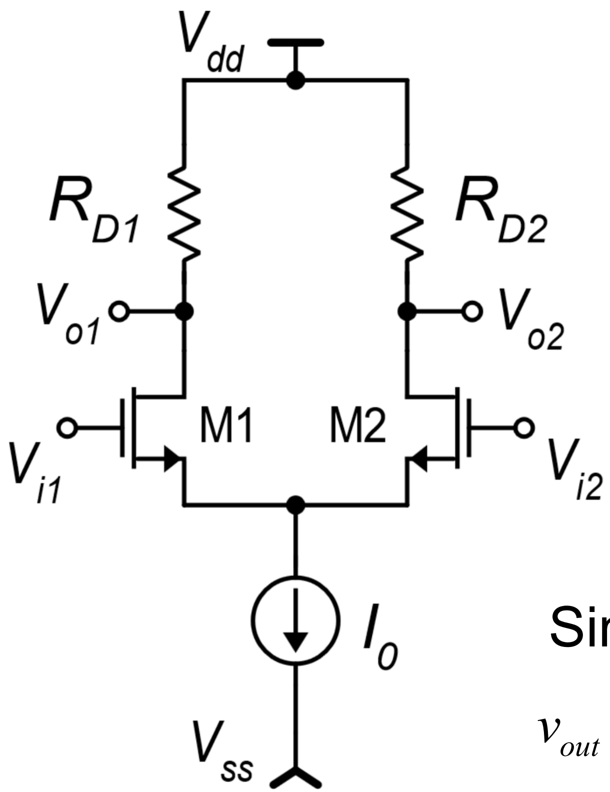
$$I_{occ} = k_I \left(I_1 - I_2 \right) = G_{m1} k_I V_{in}$$

$$v_{out} = G_{m1} k_1 v_{in} R_{out}$$

$$\text{defining: } G_m = k_I G_{m1}$$

$$A = G_m R_{out}$$

Differential amplifier with resistive loads



$$V_{ID} = V_{i1} - V_{i2} \quad V_{OD} = V_{o1} - V_{o2}$$

$$V_{O1} = V_{DD} - R_{D1} I_{D1} \quad V_{O2} = V_{DD} - R_{D2} I_{D2} \quad V_{OD} = R_{D2} I_{D2} - R_{D1} I_{D1}$$

Small signal analysis

$$v_{o1} = -R_{D1} i_{d1} \quad v_{o2} = -R_{D2} i_{d2} \quad v_{od} = i_{d2} R_{D2} - i_{d1} R_{D1}$$

Differential mode: $i_{d1} = \frac{g_m}{2} v_{id} \quad i_{d2} = -\frac{g_m}{2} v_{id}$

Single-ended case:

$$v_{out} = v_{o1} = -R_{D1} \frac{g_m}{2} v_{id}$$

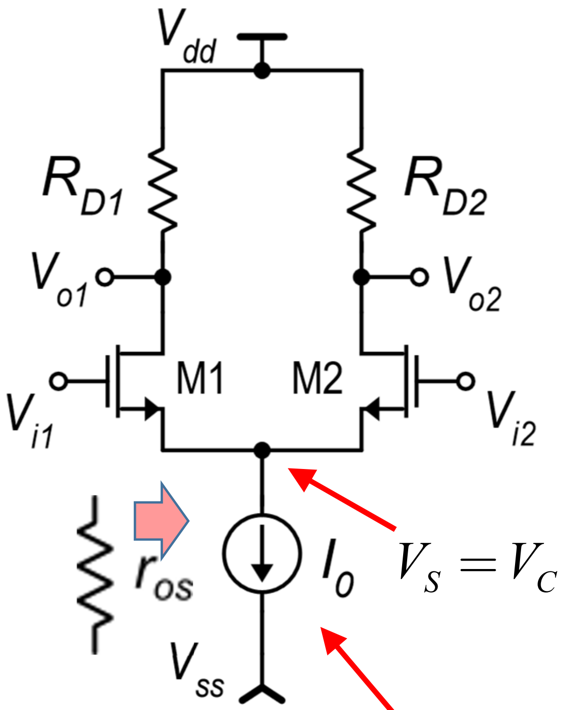
$$A_d = -R_{D1} \frac{g_m}{2}$$

Fully-differential case:

$$v_{out} = v_{od} = -\frac{g_m}{2} (R_{D1} + R_{D2}) v_{id}$$

$$A_{dd} = -g_m \frac{(R_{D1} + R_{D2})}{2}$$

Common mode Analysis



$$V_S = V_C - V_{GS}$$

$$V_{GS} \cong constant$$

$$v_{id} = 0 \quad \Rightarrow i_{d1} = i_{d2}$$

$$v_{i1} = v_{i2} = v_c$$

$$i_0 = i_{d1} + i_{d2} = \frac{v_s}{r_{os}}$$

$$v_s = v_{i1} - v_{gs1} = v_c - v_{gs1}$$

$$i_{d1} \cong g_m v_{gs1}$$

$$v_{gs1} = \frac{i_{d1}}{g_m}$$

$$v_s = v_c - \frac{i_{d1}}{g_m}$$

$$i_{d1} + i_{d2} = 2i_{d1} = i_0$$

$$i_{d1} = \frac{i_0}{2} = \frac{v_s}{2r_{os}}$$

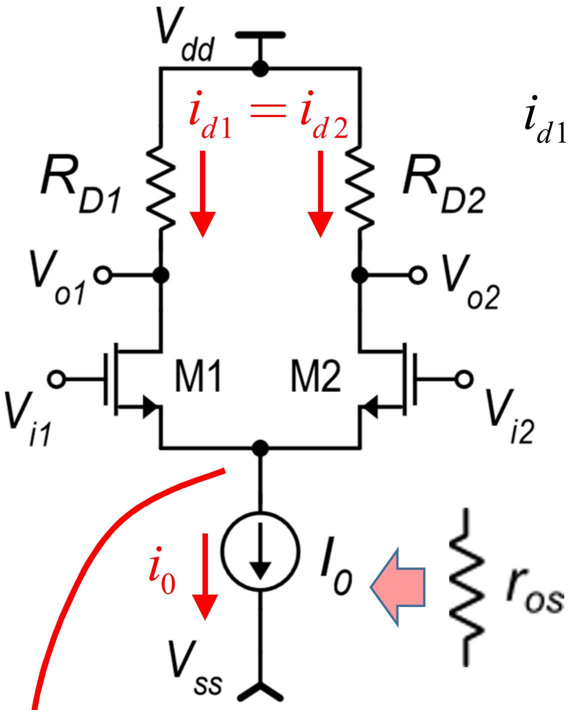
$$v_s = v_c - \frac{v_s}{2r_{os}g_m}$$

$$v_s = v_c \frac{1}{1 + \frac{1}{2g_m r_{os}}} \cong v_c$$

This, actually, is not an ideal current source. It has a finite output resistance = r_{os} If it is implemented by a simple current mirror, r_{os}= r_d otherwise it can be even higher

The source voltage practically follows the common mode variations. V_S is V_C shifted by V_{GS}

Common mode gain and CMRR



output voltages

$$i_{d1} = i_{d2} \cong \frac{i_0}{2} \qquad v_{o1} = -R_{D1} i_{d1} \quad v_{o2} = -R_{D2} i_{d2} \quad v_{od} = i_{d2} R_{D2} - i_{d1} R_{D1}$$

Single-ended case

$$v_{out} = v_{o1} = -R_{D1} i_{d1} \qquad v_{out} - R_{D1} \frac{i_0}{2} \cong -R_{D1} \frac{v_c}{2r_{os}}$$

$$A_c = \left. \frac{v_{out}}{v_c} \right|_{v_d = 0} \cong -\frac{R_{D1}}{2r_{os}} \qquad CMRR = \frac{A_d}{A_c} = \frac{g_m R_{D1}}{2} \frac{2r_{os}}{R_{D1}}$$

$|A_d|$

$$v_{i1} = v_{i2} = v_c$$

$$v_s \cong v_c$$

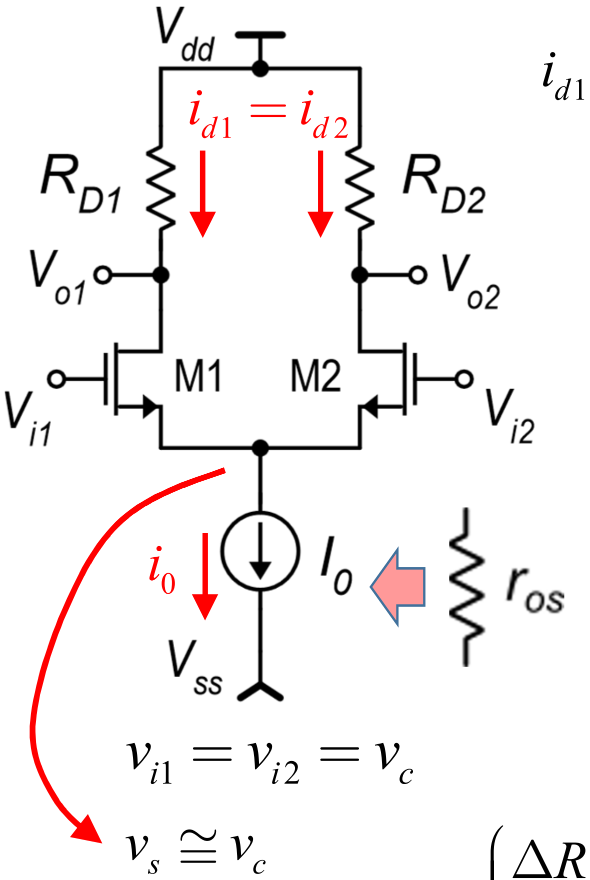
$$i_o = \frac{v_s}{r_{os}} \cong \frac{v_c}{r_{os}}$$

$$CMRR = \left| \frac{A_d}{A_c} \right| = g_m r_{os}$$

Considering that generally I_0 is produced by a simple current mirror, r_{os}=r_d, then CMRR~40 dB,

This CMRR is not sufficient for many applications

Common mode gain and CMRR



$$i_{d1} = i_{d2} \cong \frac{i_0}{2} \qquad v_{o1} = -R_{D1} i_{d1} \quad v_{o2} = -R_{D2} i_{d2} \quad v_{od} = i_{d2} R_{D2} - i_{d1} R_{D1}$$

Fully differential case

$$v_{out} = v_{od} = \frac{i_0}{2} R_{D2} - \frac{i_0}{2} R_{D1} = \frac{i_0}{2} \left(R_{D2} - R_{D1} \right)$$

$$v_{out} = \frac{v_c}{2 r_{os}} \left(R_{D2} - R_{D1} \right) \qquad A_{cd} = \left. \frac{v_{od}}{v_{ic}} \right|_{v_{id}=0} = -\frac{1}{2 r_{os}} \left(R_{D1} - R_{D2} \right)$$

$$CMRR = \left| \frac{A_{dd}}{A_{cd}} \right| = \frac{g_m (R_{D1} + R_{D2})}{2} \frac{2 r_{os}}{(R_{D1} - R_{D2})} = 2 g_m r_{os} \left(\frac{\Delta R_D}{R_D} \right)^{-1}$$

$\bar{R}_D$ $\quad \Delta R_D$

$v_{i1} = v_{i2} = v_c$

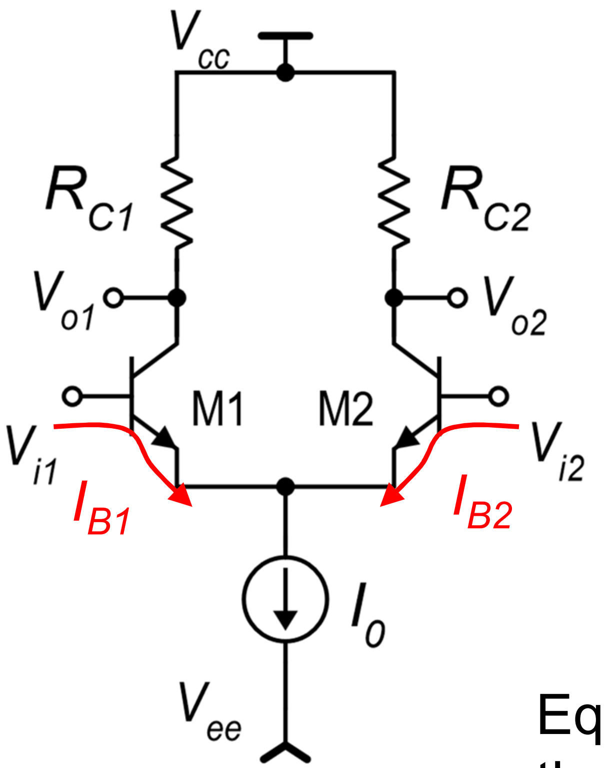
$v_s \cong v_c$

$\left(\frac{\Delta R_D}{R_D} \right)$ is a relative matching error ~ 0.01 $\Rightarrow \left(\frac{\Delta R_D}{R_D} \right)^{-1} \approx 100$

$CMRR \approx 10^4 = 80\,\text{dB}$

Adequate for most applications

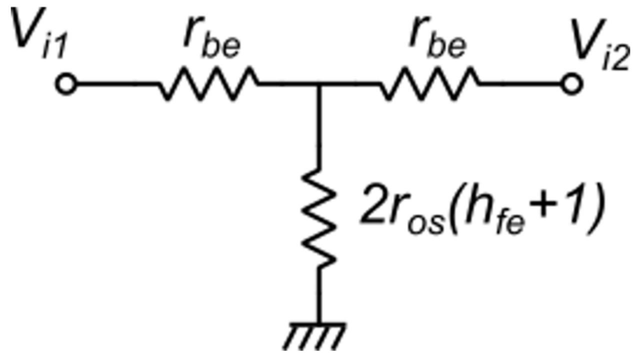
BJT case



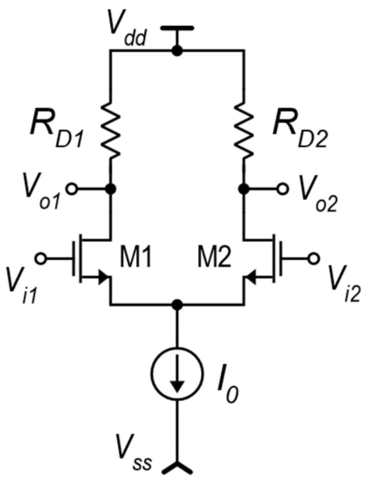
In the case of a BJT differential amplifier, the expressions are exactly the same as for the MOSFET case.

The only important difference is the presence of a base current that is drawn from the voltage sources that provide V_{i1} and V_{i2}. In terms of small signal analysis, this base current is the cause of a finite input resistance that may result in an input attenuation if the signal voltage sources (V_{i1}, V_{i2}) have a significant internal resistance.

Equivalent circuit of the input terminals



Maximum gain for a given supply voltage



single ended $A_d = -R_{D1}\dfrac{g_m}{2}$ $\qquad |A_d| = \dfrac{g_m R_D}{2}$

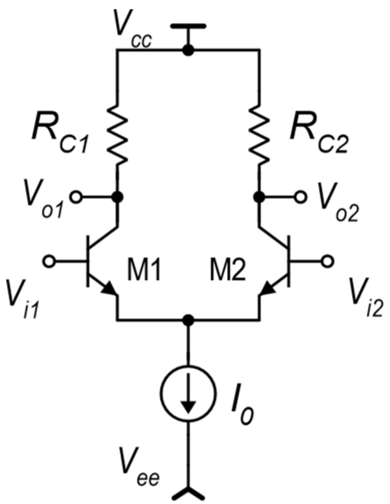
fully-differential $A_{dd} = -g_m\dfrac{(R_{D1}+R_{D2})}{2}$ $\qquad |A_{dd}| = g_m R_D$

nominal case: $R_{D1}=R_{D2}=R_D$

using: $g_m = \dfrac{I_D}{V_{TE}}$ $\qquad |A_{dd}| = \dfrac{R_D I_D}{V_{TE}}$

$R_D I_D$ is the static voltage drop across resistors R_D. It cannot exceed the total supply voltage $V_{DD}-V_{SS}$

$$R_D I_D < (V_{DD} - V_{SS})$$



$$|A_{dd}| < \frac{(V_{DD} - V_{SS})}{V_{TE}}$$

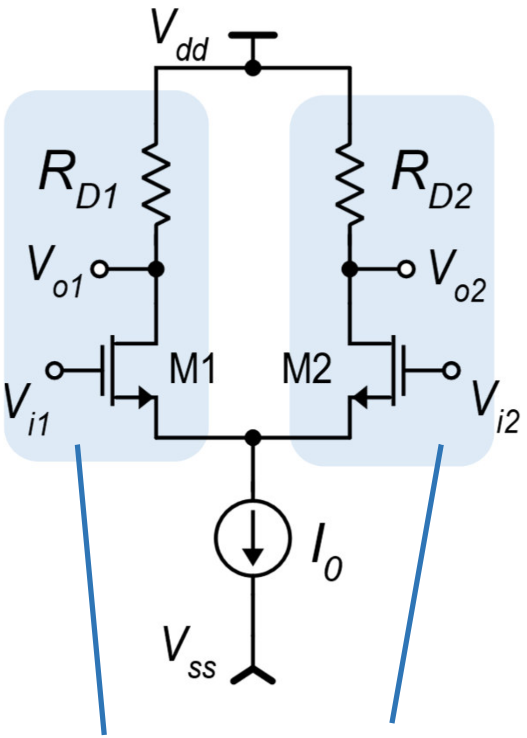
Example: V_{TE}=50 mV, V_{DD}-V_{SS}=3 V: $|A_{dd}| < 60$

With a BJT: $V_{TE}=V_T$=25 mV: $|A_{dd}| < 120$

To get the highest gain for a given supply voltage it is convenient to bias the MOSFETS with the smallest V_{TE}.

Offset voltage of differential amplifiers with resistive load

MOSFET case - fully-differential - Strong inversion



Nominally identical circuits

$$v_{io} = V_D\Big|_{V_{out}=0} \qquad V_D = V_{GS1} - V_{GS2} \triangleq \Delta V_{GS}$$

$$V_{out} = V_{o1} - V_{o2}$$

We can consider the difference of V_{GS} as the matching error between two nominally identical circuits: M1,R_{D1} and M2,R_{D2}

$$V_{GS} = V_t + \sqrt{\frac{2I_D}{\beta}} \qquad A = V_t \quad B = \sqrt{\frac{2I_D}{\beta}} = \sqrt{2}\cdot I_D^{\frac{1}{2}}\beta^{-\frac{1}{2}}$$

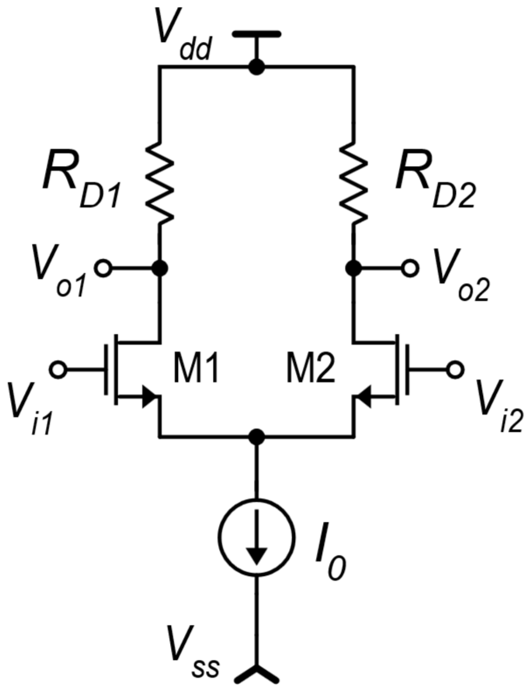
posynomial form

$$V_{GS} = A + B \qquad \Delta V_{GS} = \Delta A + \Delta B$$

$$\Delta A = \Delta V_t \qquad \Delta B = B\cdot\frac{\Delta B}{B} = B\cdot\left(\frac{1}{2}\frac{\Delta I_D}{I_D} - \frac{1}{2}\frac{\Delta\beta}{\beta}\right)$$

Offset voltage of differential amplifiers with resistive load

MOSFET case - fully-differential



$$V_D = \Delta V_{GS} = \Delta A + \Delta B \qquad V_{GS} = \underbrace{V_t}_{A} + \overbrace{\sqrt{\frac{2I_D}{\beta}}}^{B}$$

$$\Delta A = \Delta V_t \qquad \Delta B = B \cdot \left(\frac{1}{2}\frac{\Delta I_D}{I_D} - \frac{1}{2}\frac{\Delta \beta}{\beta} \right)$$

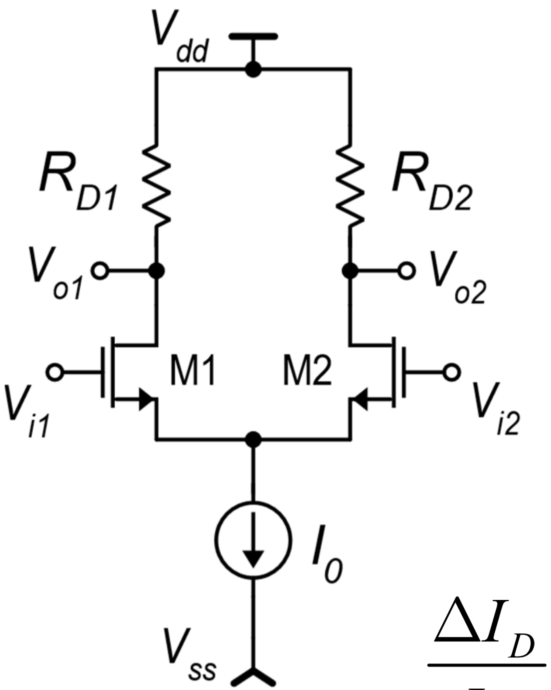
$$V_D = \Delta V_{GS} = \Delta V_t + \sqrt{\frac{2I_D}{\beta}} \cdot \left(\frac{1}{2}\frac{\Delta I_D}{I_D} - \frac{1}{2}\frac{\Delta \beta}{\beta} \right)$$

This is a generic expression of V_D, corresponding to a given value of $\frac{\Delta I_D}{I_D}$

This expression gives V_{io} for the particular $\frac{\Delta I_D}{I_D}$ value that results in V_{out}=0

Offset voltage of differential amplifiers with resistive load

MOSFET case - fully-differential



$$V_{out} = V_{OD} = \underbrace{R_{D2}I_{D2} - R_{D1}I_{D1}}$$

defining: $Z = R_D I_D$ $\quad \Delta Z = V_{out}$

Imposing V_{out}=0 is the same as imposing ΔZ=0

$$\Delta Z = \frac{\Delta Z}{Z} Z = \underbrace{\left(\frac{\Delta R_D}{R_D} + \frac{\Delta I_D}{I_D} \right)}_{=0} R_D I_D = 0$$

$R_D I_D$ is the average value and cannot be zero

$$\frac{\Delta I_D}{I_D} = -\frac{\Delta R_D}{R_D}$$

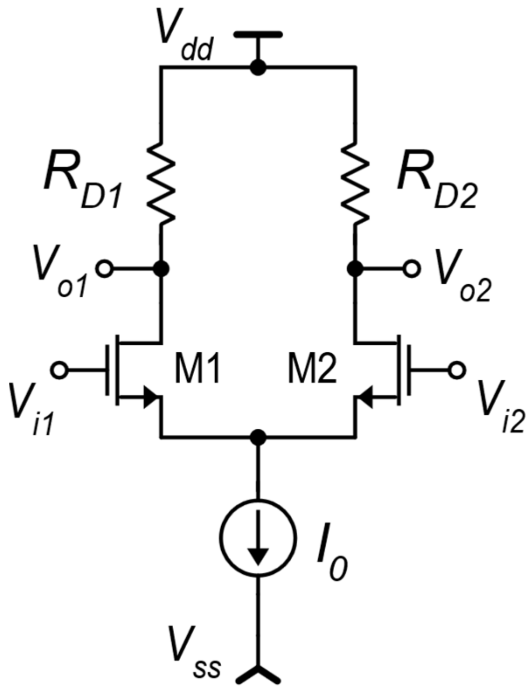
$$V_D = \Delta V_{GS} = \Delta V_t + \sqrt{\frac{2I_D}{\beta}} \cdot \left(\frac{1}{2} \frac{\Delta I_D}{I_D} - \frac{1}{2} \frac{\Delta \beta}{\beta} \right)$$

$$-\frac{\Delta R_D}{R_D}$$

$$V_{io} = \Delta V_t + \sqrt{\frac{2I_D}{\beta}} \cdot \left(-\frac{1}{2} \frac{\Delta R_D}{R_D} - \frac{1}{2} \frac{\Delta \beta}{\beta} \right)$$

Offset voltage of differential amplifiers with resistive load

MOSFET case - fully-differential



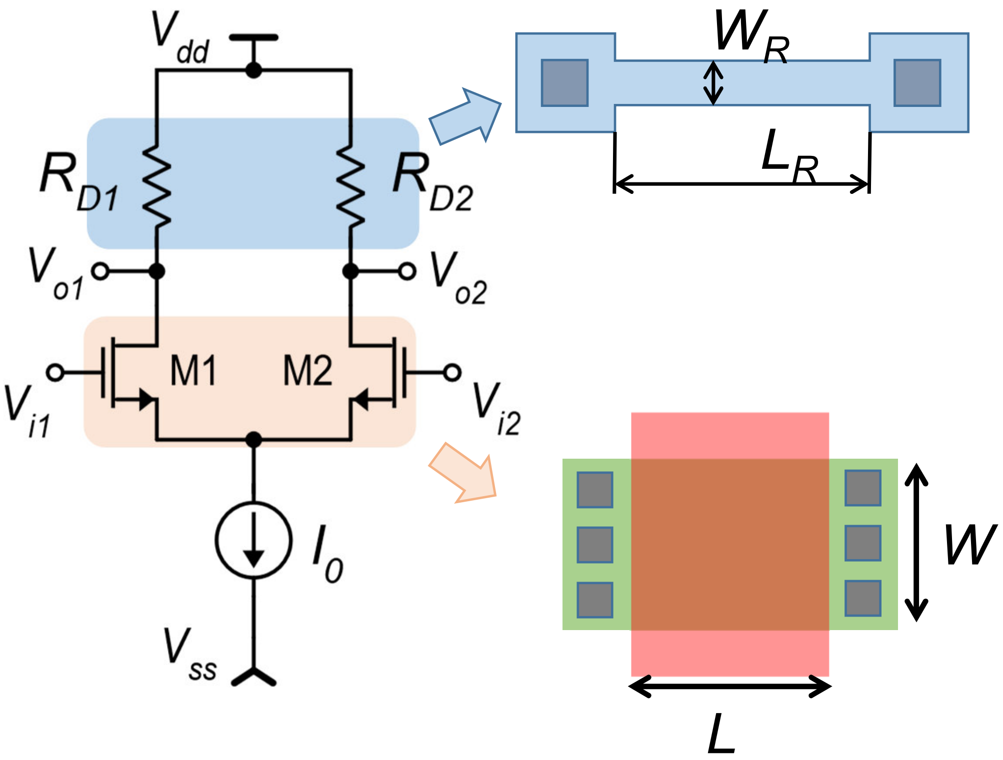
$$V_{io} = \Delta V_t + \sqrt{\frac{2I_D}{\beta}} \cdot \left(-\frac{1}{2}\frac{\Delta R_D}{R_D} - \frac{1}{2}\frac{\Delta \beta}{\beta} \right)$$

$$V_{io} = \Delta V_t - \frac{(V_{GS} - V_t)}{2}\left(\frac{\Delta R_D}{R_D} + \frac{\Delta \beta}{\beta} \right)$$

$$\sigma_{Vio} = \sqrt{\sigma_{Vt}^2 + \left[\sigma_{\frac{\Delta\beta}{\beta}} \frac{(V_{GS} - V_t)}{2}\right]^2 + \left[\sigma_{\frac{\Delta R_D}{R_D}} \frac{(V_{GS} - V_t)}{2}\right]^2}$$

Role of the design parameters

$$\sigma_{Vio} = \sqrt{\sigma_{Vt}^2 + \left[\sigma_{\frac{\Delta\beta}{\beta}} \frac{(V_{GS}-V_t)}{2}\right]^2 + \left[\sigma_{\frac{\Delta R_D}{R_D}} \frac{(V_{GS}-V_t)}{2}\right]^2}$$



$$\frac{L_R}{W_R} \rightarrow R_D \qquad W_R L_R \rightarrow \sigma_{\frac{\Delta R_D}{R_D}} = \frac{C_R}{\sqrt{W_R L_R}}$$

To be made as small as possible, to reduce σ_{Vio}

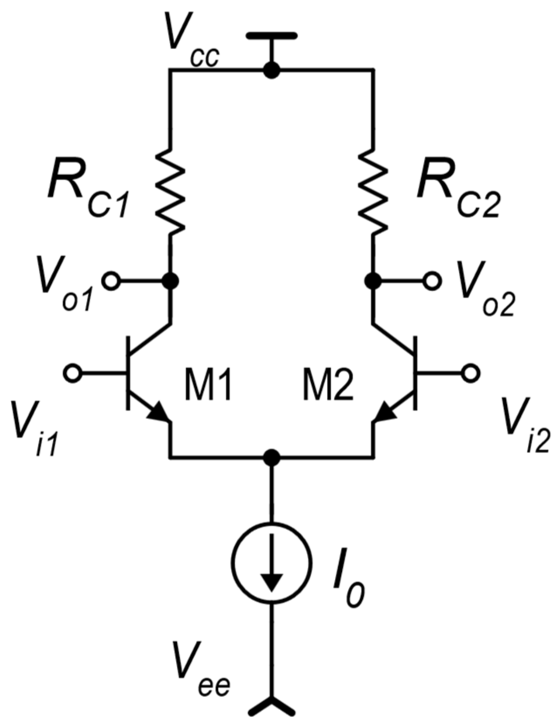
$$I_0 \rightarrow (V_{GS} - V_t)$$

$$\frac{W}{L} \rightarrow \beta$$

$$WL \rightarrow \begin{cases} \sigma_{Vt} = \dfrac{C_{vt}}{\sqrt{WL}} \\ \sigma_{\frac{\Delta\beta}{\beta}} = \dfrac{C_\beta}{\sqrt{WL}} \end{cases}$$

Small offset means large silicon area

Offset voltage of a BJT differential amplifier with resistor load



$$v_{io} = V_{id}\big|_{V_{od}=0} \qquad V_{od} = V_{o1} - V_{o2} = R_{C2}I_{C2} - R_{C2}I_{C2}$$

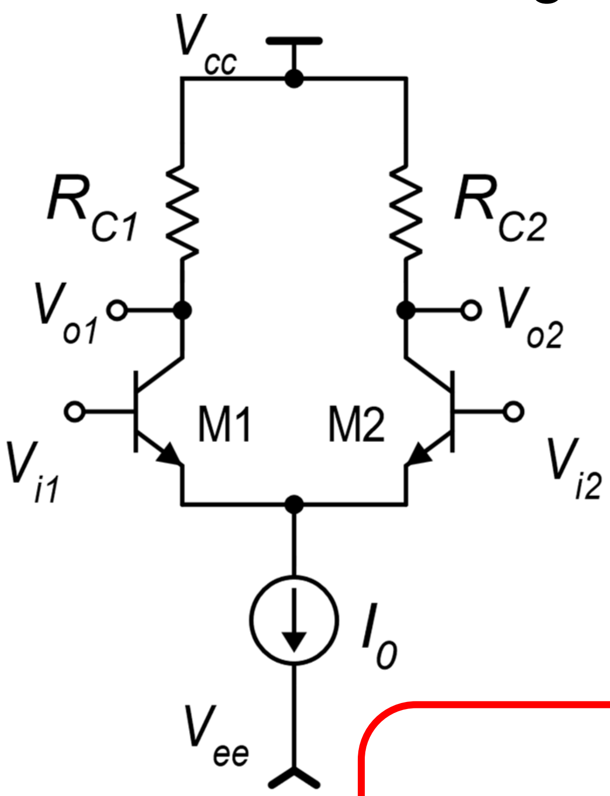
$$V_{id} = V_{i1} - V_{i2} = V_{BE1} - V_{BE2} = \Delta V_{BE}$$

$$V_{BE} = V_T \ln\left(\frac{I_C}{I_S}\right) \qquad V_{id} = \Delta V_{BE} = V_T\left(\frac{\Delta I_C}{I_C} - \frac{\Delta I_S}{I_S}\right)$$

$$V_{od} = 0 \Rightarrow \Delta\left(R_C I_C\right) = 0 \Rightarrow \frac{\Delta I_C}{I_C} = -\frac{\Delta R_C}{R_C}$$

$$v_{io} = V_T\left(-\frac{\Delta R_C}{R_C} - \frac{\Delta I_S}{I_S}\right)$$

Offset voltage of a BJT differential amplifier with resistor load



$$v_{io} = V_T\left(-\frac{\Delta R_C}{R_C} - \frac{\Delta I_S}{I_S}\right)$$

$$\sigma_{vio} = \sqrt{\left(V_T \sigma_{\frac{\Delta R_C}{R_C}}\right)^2 + \left(V_T \sigma_{\frac{\Delta I_S}{I_S}}\right)^2}$$

$$V_T \sigma_{\frac{\Delta I_S}{I_S}} = \sigma_{\Delta V_{BE}^*}$$

$$\sigma_{\frac{\Delta R_C}{R_C}} = \frac{C_R}{\sqrt{W_R L_R}}$$

Minimum size BJT (elemental BJT) of the process

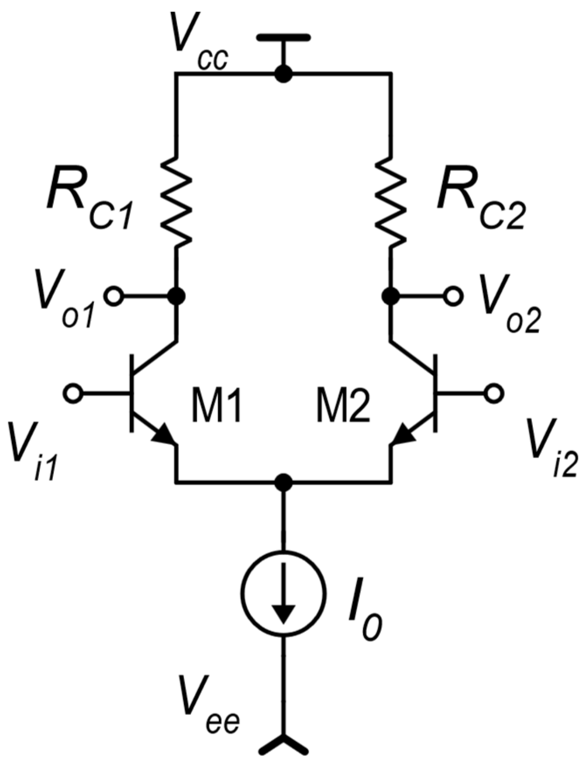
$$\sigma_{\Delta V_{BE-e}^*}$$

$$\sigma_{vio} = \sqrt{\left(V_T \sigma_{\frac{\Delta R_C}{R_C}}\right)^2 + \sigma_{\Delta V_{BE}^*}^2}$$

Small offset means large silicon area

$$\sigma_{\Delta V_{BE}^*} = \frac{\sigma_{\Delta V_{BE-e}^*}}{\sqrt{area}}$$

Temperature drift of the input offset voltage: BJT case



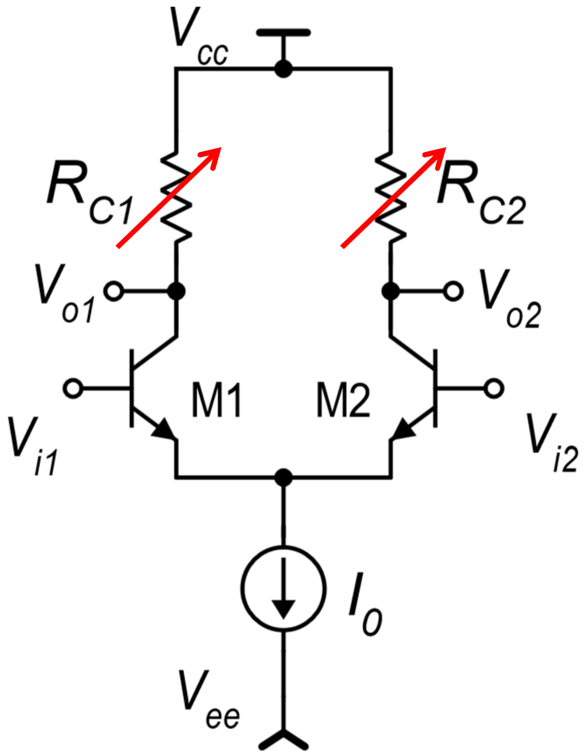
$$v_{io} = \frac{kT}{q}\left(-\frac{\Delta R_C}{R_C} - \frac{\Delta I_S}{I_S}\right)$$

These terms are practically temperature independent (ratios of homogeneous quantities)

$$\frac{dv_{io}}{dT} = \frac{k}{q}\left(-\frac{\Delta R_C}{R_C} - \frac{\Delta I_S}{I_S}\right)$$

$$\frac{dv_{io}}{dT} = \frac{kT}{q}\left(-\frac{\Delta R_C}{R_C} - \frac{\Delta I_S}{I_S}\right)\frac{1}{T} = \frac{v_{io}}{T}$$

A method to reduce the offset voltage and its drift



$$\frac{dv_{io}}{dT} = \frac{v_{io}}{T}$$

Example: v_{io}=1 mV
T=300 K

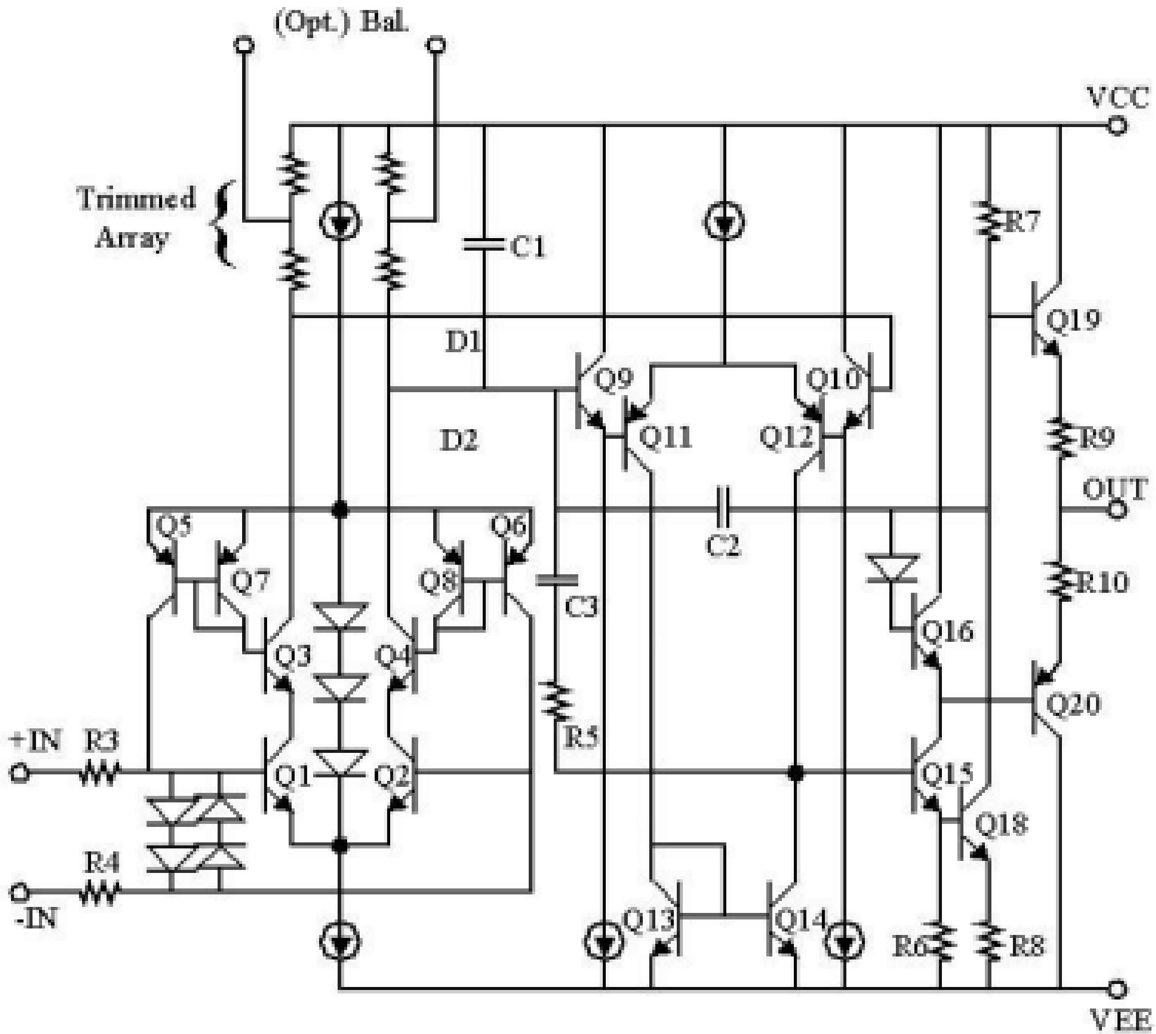
$$\frac{dv_{io}}{dT} = \frac{1.0\times10^{-3}}{300} = 3.3\ \mu\text{V/K}$$

By trimming the resistors, I can null the offset. In this way, also the temperature drift is nulled.

This is an advantage of the BJT amplifier. Trimming the offset of a MOSFET differential amplifier does not null the drift.

Example: the OP07

1. Resistors are varied by laser trimming to null the offset
2. In this way, also the offset drift is strongly reduced
3. The base currents of the input devices (Q1,Q2) are reproduced by Q3 and Q4 and than fed back to the input terminals by mirrors Q8,Q6 and Q7,Q5. This approach allows to reduce the input bias currents.



OP07 vs µA741

OP07

Table 1.

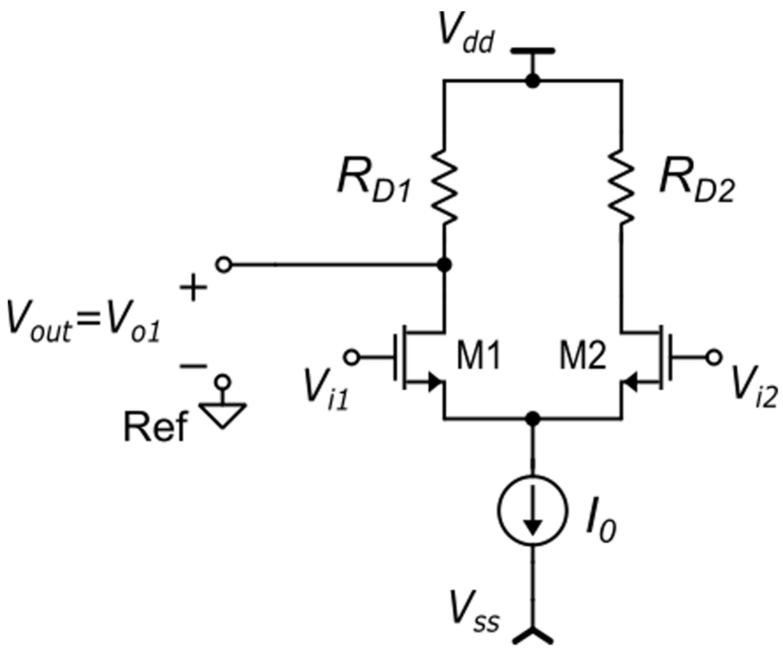
Parameter	Symbol	Conditions	Min	Typ	Max	Unit
INPUT CHARACTERISTICS						
T_A = 25°C						
Input Offset Voltage[1]	V_{OS}			30	75	µV
Long-Term V_{OS} Stability[2]	V_{OS}/Time			0.3	1.5	µV/Month
Input Offset Current	I_{OS}			0.5	3.8	nA
Input Bias Current	I_B			±1.2	±4.0	nA
0°C ≤ T_A ≤ 70°C						
Input Offset Voltage[1]	V_{OS}			45	130	µV
Voltage Drift Without External Trim[4]	TCV_{OS}			0.3	1.3	µV/°C
Voltage Drift with External Trim[3]	TCV_{OSN}	R_P = 20 kΩ		0.3	1.3	µV/°C

µA741

at specified virtual junction temperature, $V_{CC\pm}$ = ±15 V (unless otherwise noted)

PARAMETER		TEST CONDITIONS[(1)]		MIN	TYP	MAX	UNIT
V_{IO}	Input offset voltage	V_O = 0	25°C		1	6	mV
			Full range			7.5	
$\Delta V_{IO(adj)}$	Offset voltage adjust range	V_O = 0	25°C		±15		mV
I_{IO}	Input offset current	V_O = 0	25°C		20	200	nA
			Full range			300	
I_{IB}	Input bias current	V_O = 0	25°C		80	500	nA
			Full range			800	

How is the amplifier offset when the single ended option is chosen?



$$V_{out} = V_{O1} = V_{dd} - R_1 I_{D1}$$

Single ended (S/E): device parameters do not appear as differences: the output voltage is affected mainly by global errors

The single ended case is subjected to a much larger offset!

Compare with the fully-differential case: the output voltage depends only on matching differences

$$V_{od} = R_{D2} I_{D2} - R_{D1} I_{D1}$$