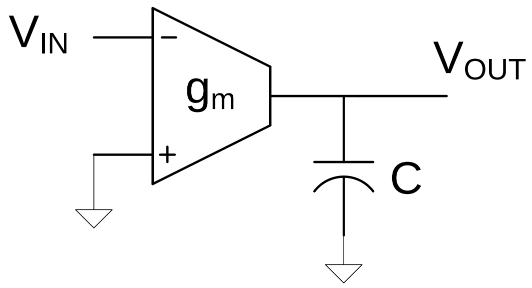
EE 508

Lecture 34

Transconductor Design

Transconductor Design



Transconductor-based filters depend directly on the g_m of the transconductor

Feedback is not used to make the filter performance insensitive to the transconductance gain

Linearity and spectral performance of the filter strongly dependent upon the linearity of the transconductor

Often can not justify elegant linearization strategies in the transconductors because of speed, area, and power penalties

Seminal Work on the OTA

RCA

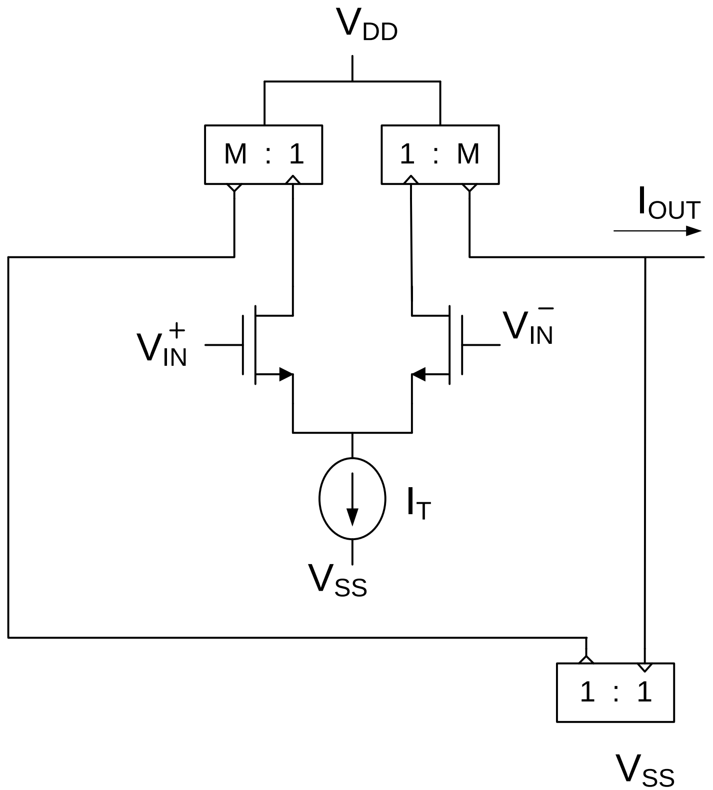
OTA Obsoletes Op Amp

by C. F. Wheatley
H. A. Wittlinger

From:

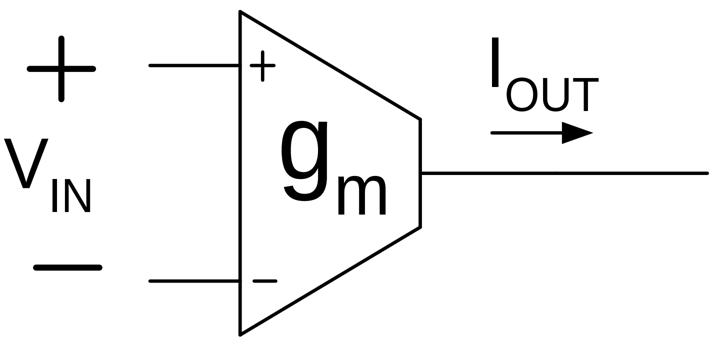
1969 N.E.C. PROCEEDINGS
December 1969

Current Mirror Op Amp W/O CMFB



$$g_{mEQ} = Mg_{m1}$$

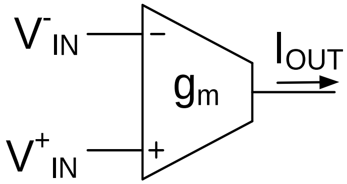
Often termed an OTA

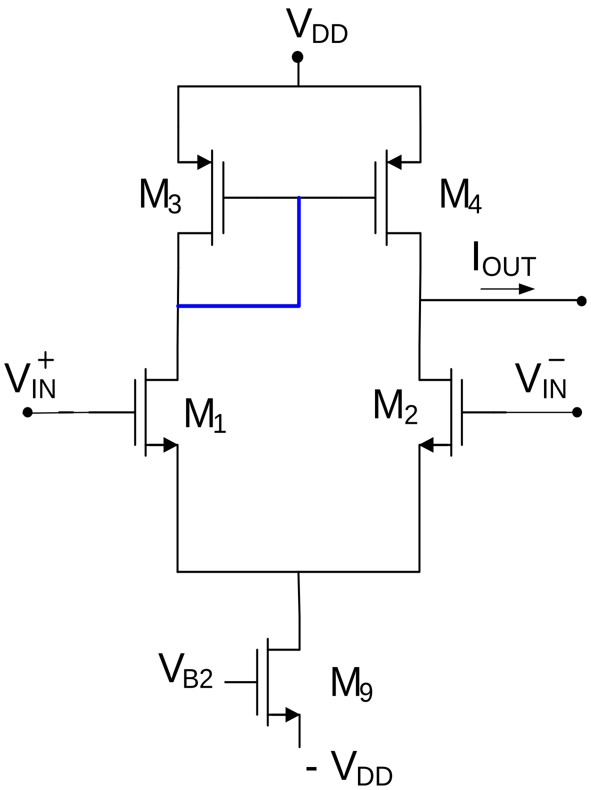


Introduced by Wheatley and Whitlinger in 1969

$$I_{OUT} = g_m V_{IN}$$

Basic OTA based upon differential pair

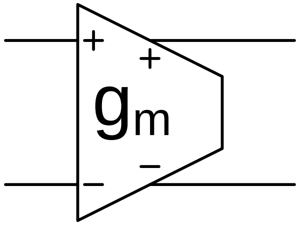


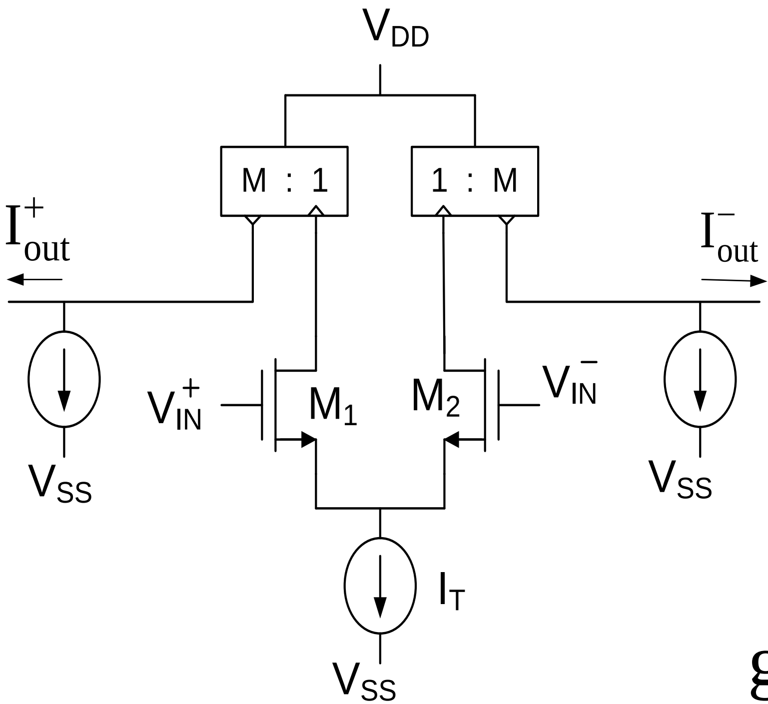


$$g_m = g_{m1}$$

Assume M_1 and M_2 matched,
M_3 and M_4 matched

Differential output OTA based upon differential pair

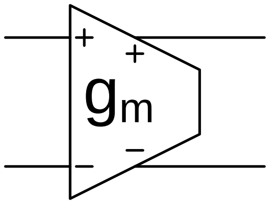


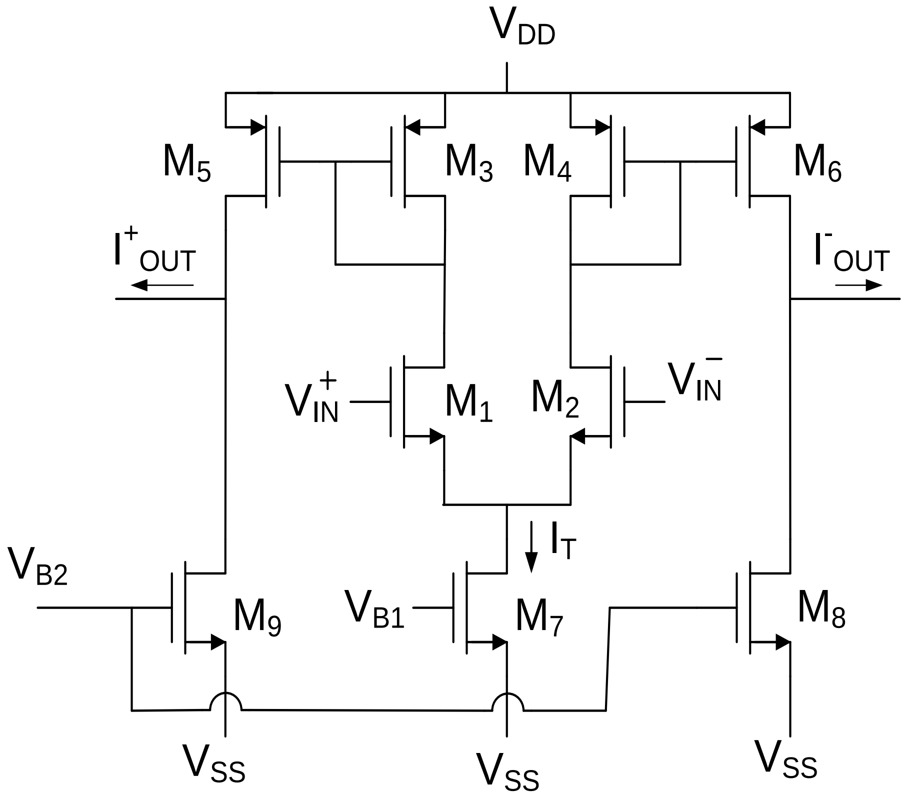


$$g_m = \frac{g_{m1}}{2} M$$

CMFB needed for the two output biasing current sources

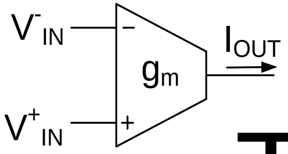
Differential output OTA based upon differential pair



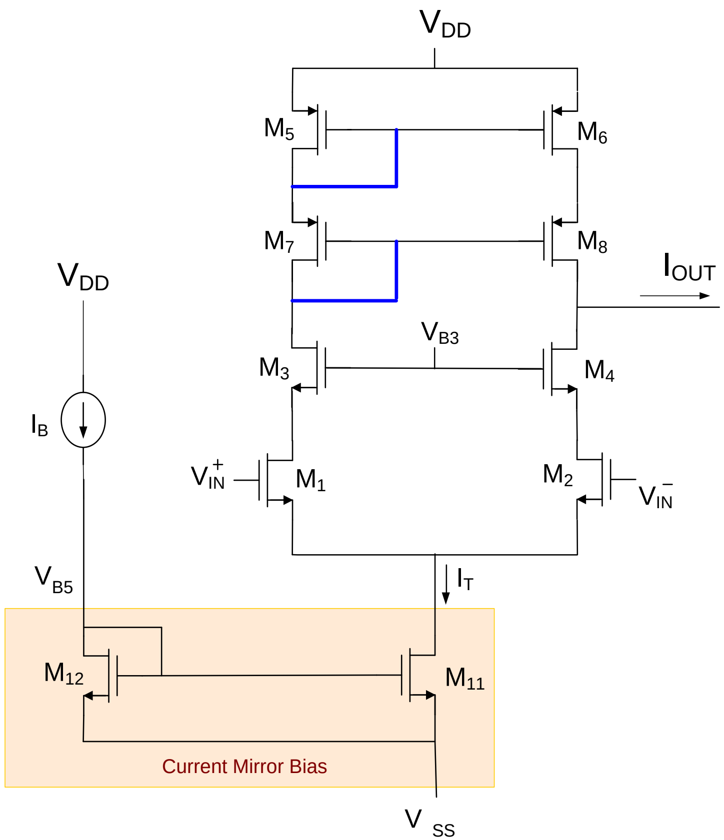


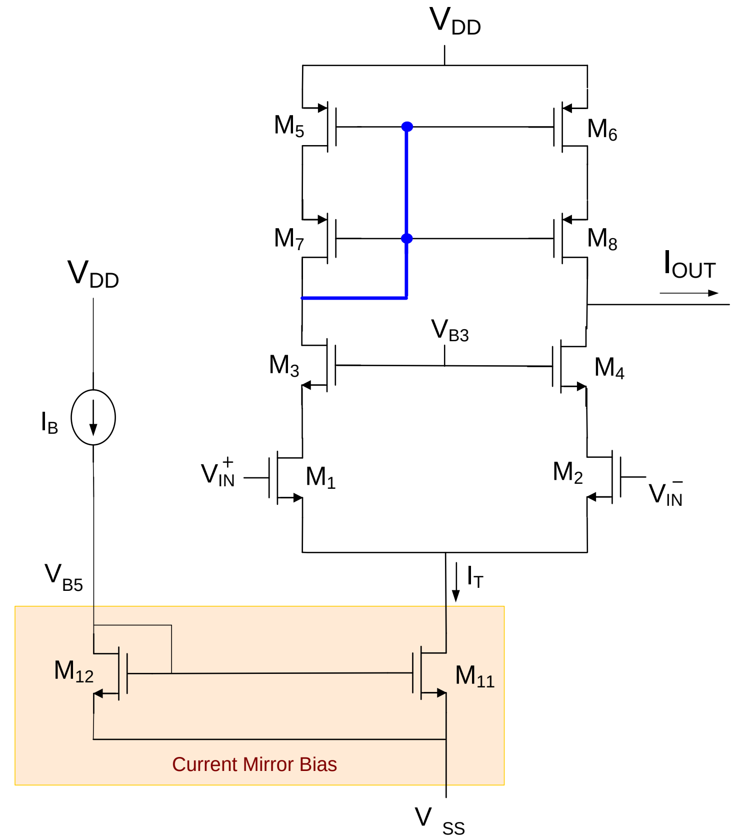
$$g_m = \frac{g_{m1}}{2} M$$

CMFB needed for the two output biasing current sources



Telescopic Cascode OTA



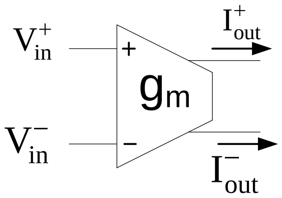


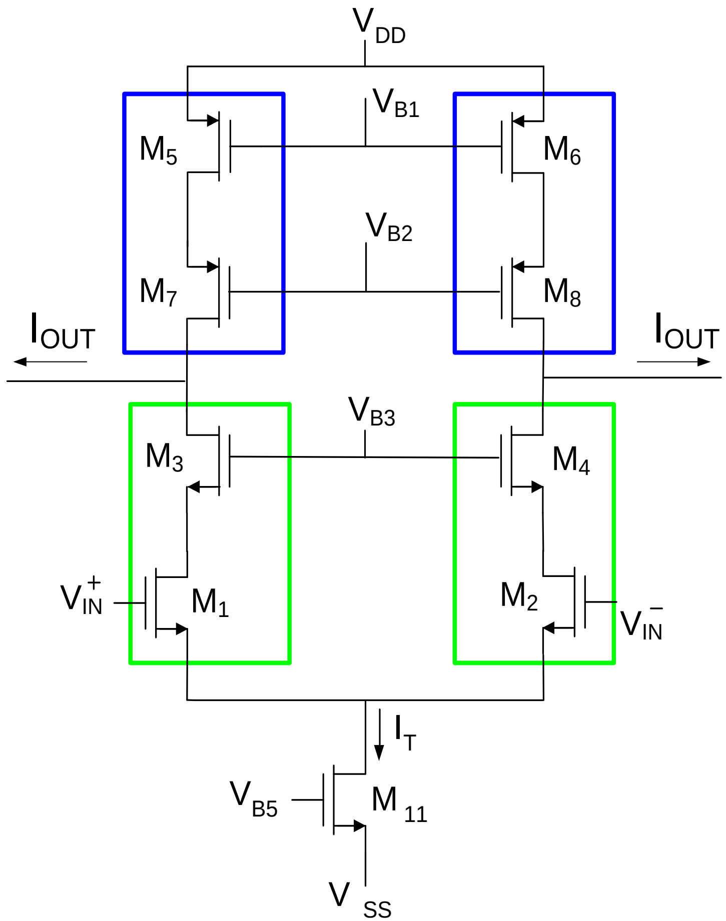
Standard p-channel Cascode Mirror

Wide-Swing p-channel Cascode Mirror

- Current-Mirror p-channel Bias to Eliminate CMFB
- Only single-ended output available

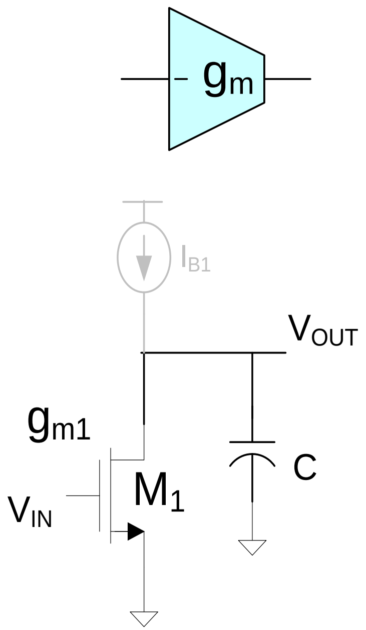
Telescopic Cascode OTA



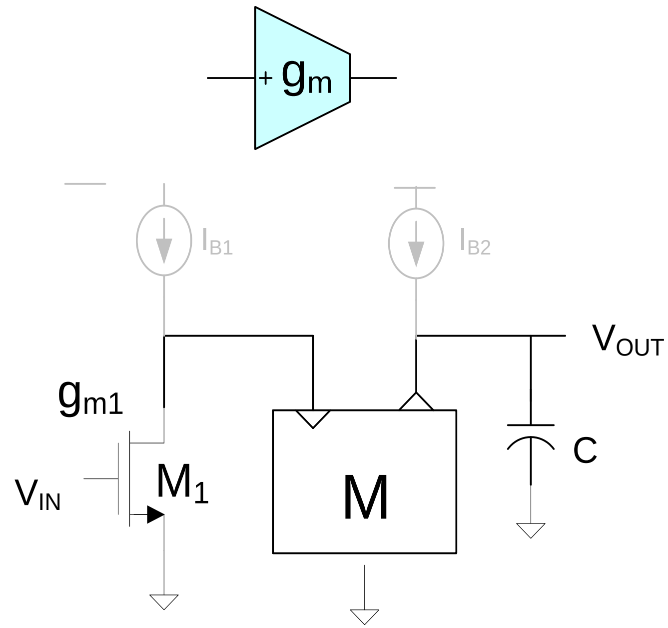


CMFB needed

Single-ended High-Frequency TA

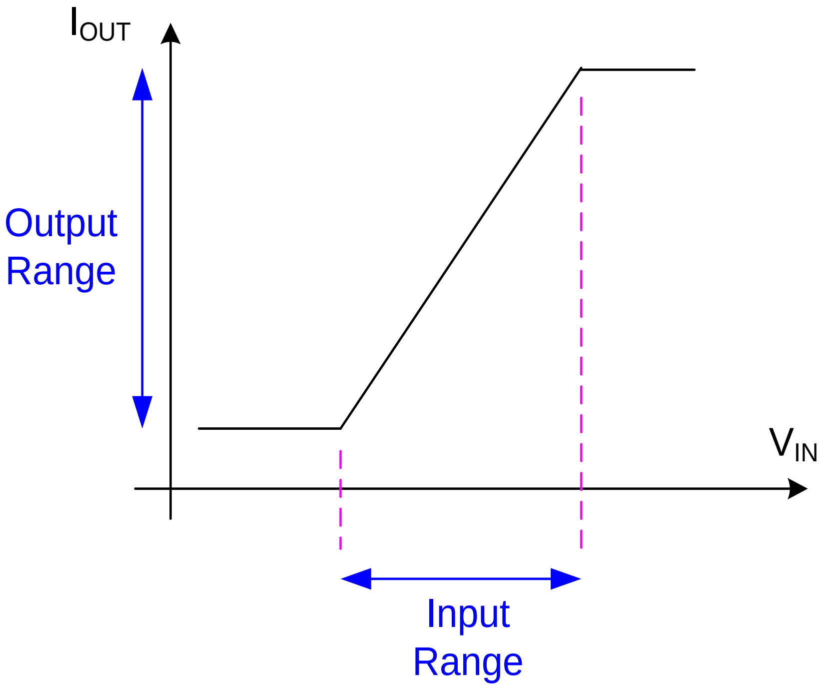


$$g_m = -g_{m1}$$



$$g_m = M g_{m1}$$

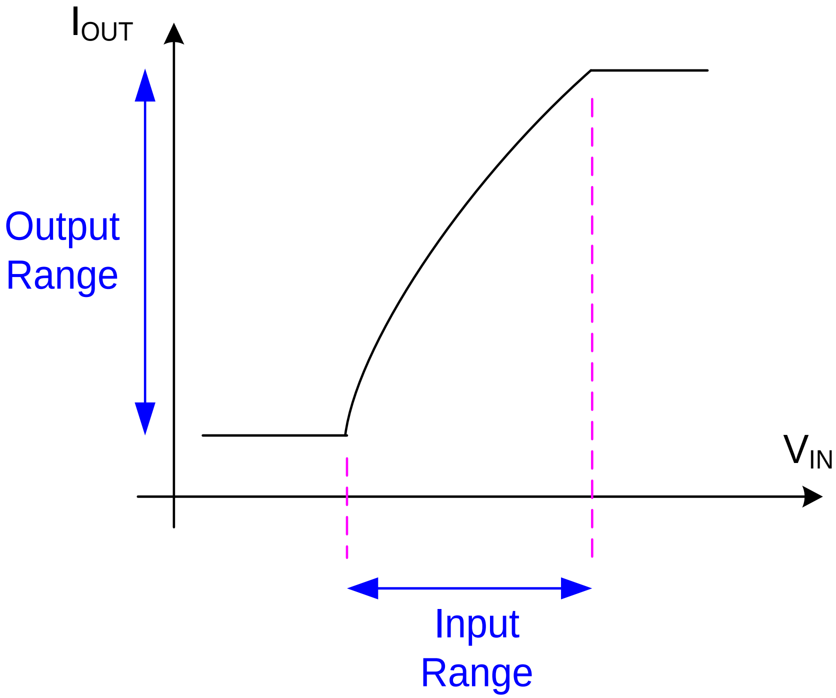
Signal Swing and Linearity



Ideal Scenario:

Completely Linear over Input and Output Range

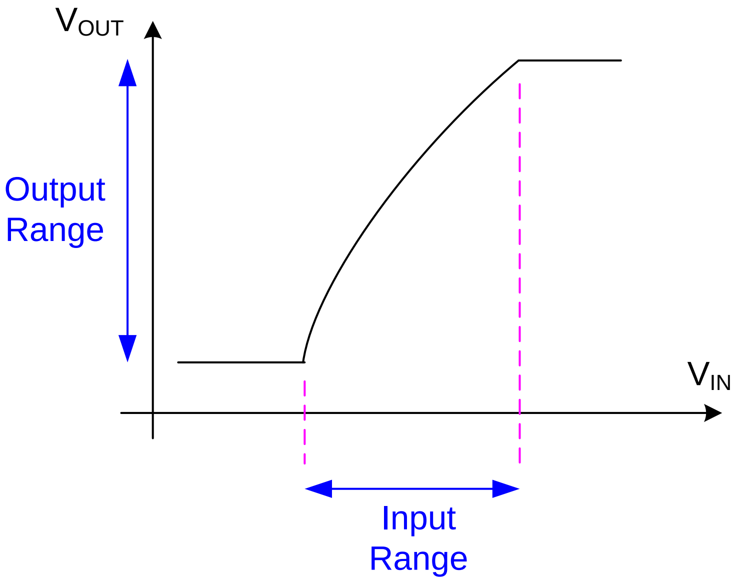
Signal Swing and Linearity

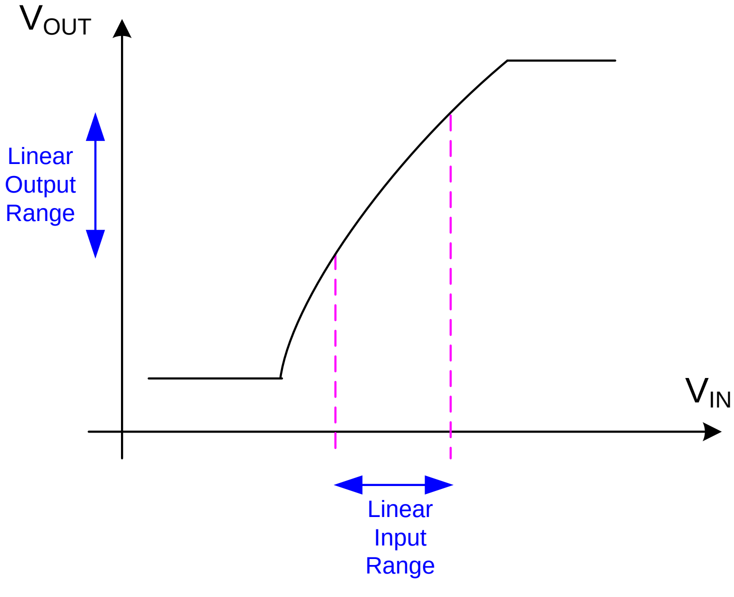


Realistic Scenario:

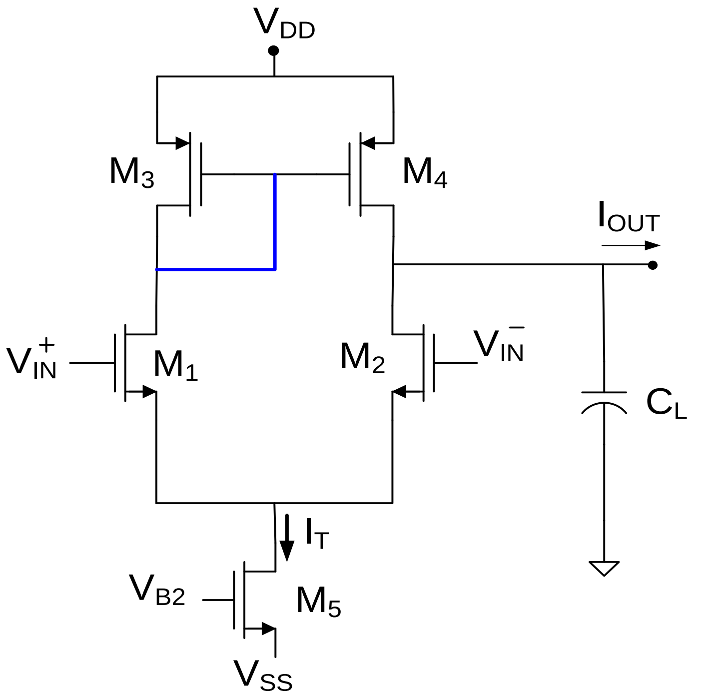
- Modest Nonlinearity throughout Input Range
- But operation will be quite linear over subset of this range

Signal Swing and Linearity



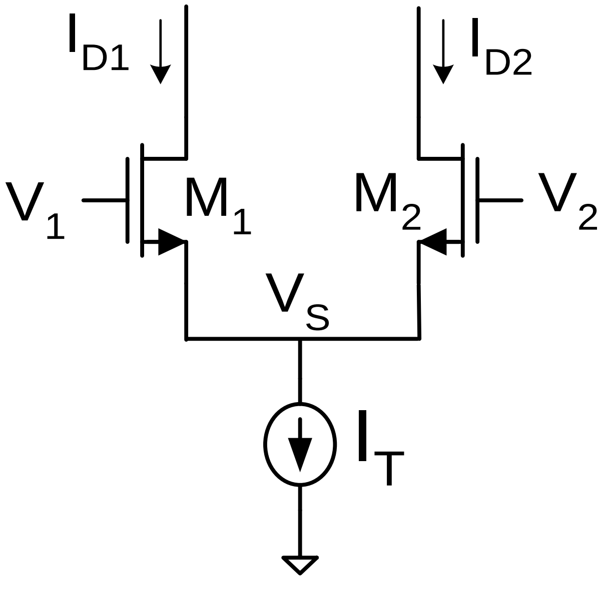


Linearity of Amplifiers

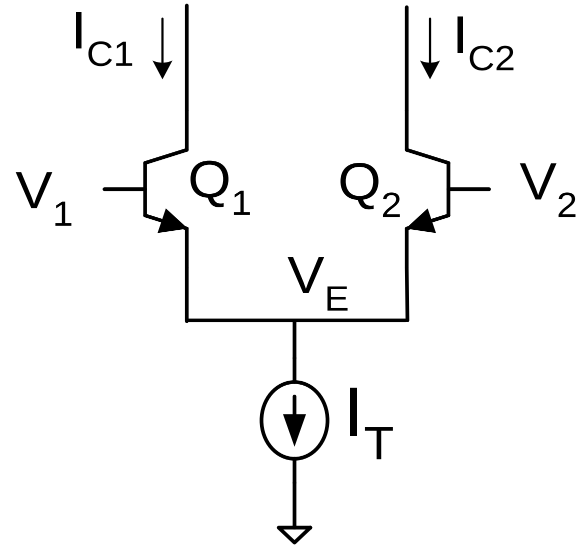


Strongly dependent upon linearity of transconductance of differential pair

Differential Input Pairs

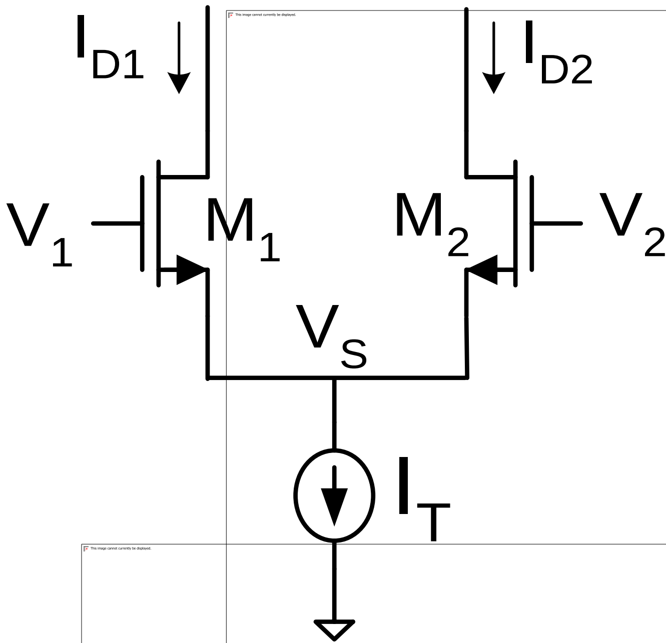


MOS Differential Pair



Bipolar Differential Pair

MOS Differential Pair



$$I_{D1} = \frac{\mu C_{OX} W}{2L}(V_1 - V_S - V_T)^2$$

$$I_{D2} = \frac{\mu C_{OX} W}{2L}(V_2 - V_S - V_T)^2$$

$$I_{D1} + I_{D2} = I_T$$

$$\sqrt{I_{D1}}\sqrt{\frac{2L}{\mu C_{OX} W}} = V_1 - V_S - V_T$$

$$\sqrt{I_{D2}}\sqrt{\frac{2L}{\mu C_{OX} W}} = V_2 - V_S - V_T$$

$$V_d = V_2 - V_1$$

$$V_d = \sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_T - I_{D1}} - \sqrt{I_{D1}}\right)$$

$$V_d = \sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_{D2}} - \sqrt{I_T - I_{D2}}\right)$$

MOS Differential Pair

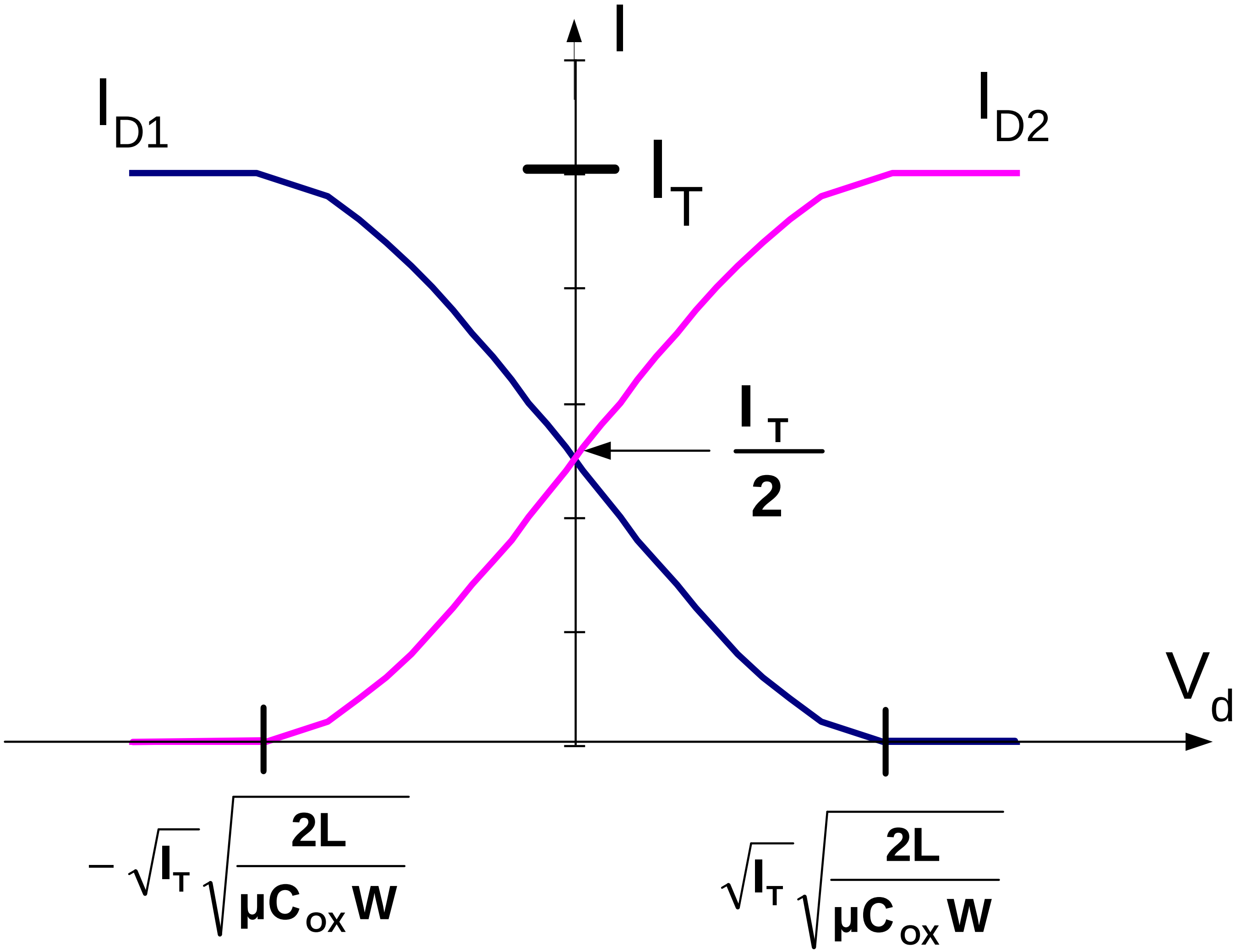
$$V_d = \sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_T - I_{D1}} - \sqrt{I_{D1}}\right)$$

$$V_d = \sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_{D2}} - \sqrt{I_T - I_{D2}}\right)$$

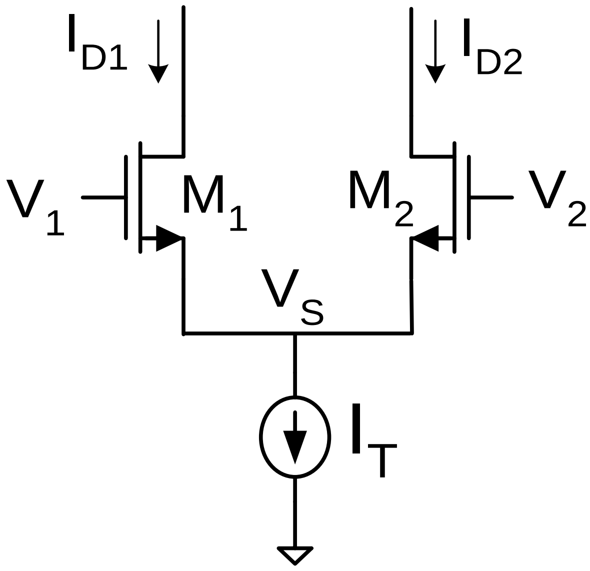
What values of V_d will cause all of the current to be steered to the left or the right ?

$$V_{dx} = \pm\sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_T}\right)$$

$$V_d = \sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_{D2}} - \sqrt{I_T - I_{D2}}\right)$$



Q-point Calculations



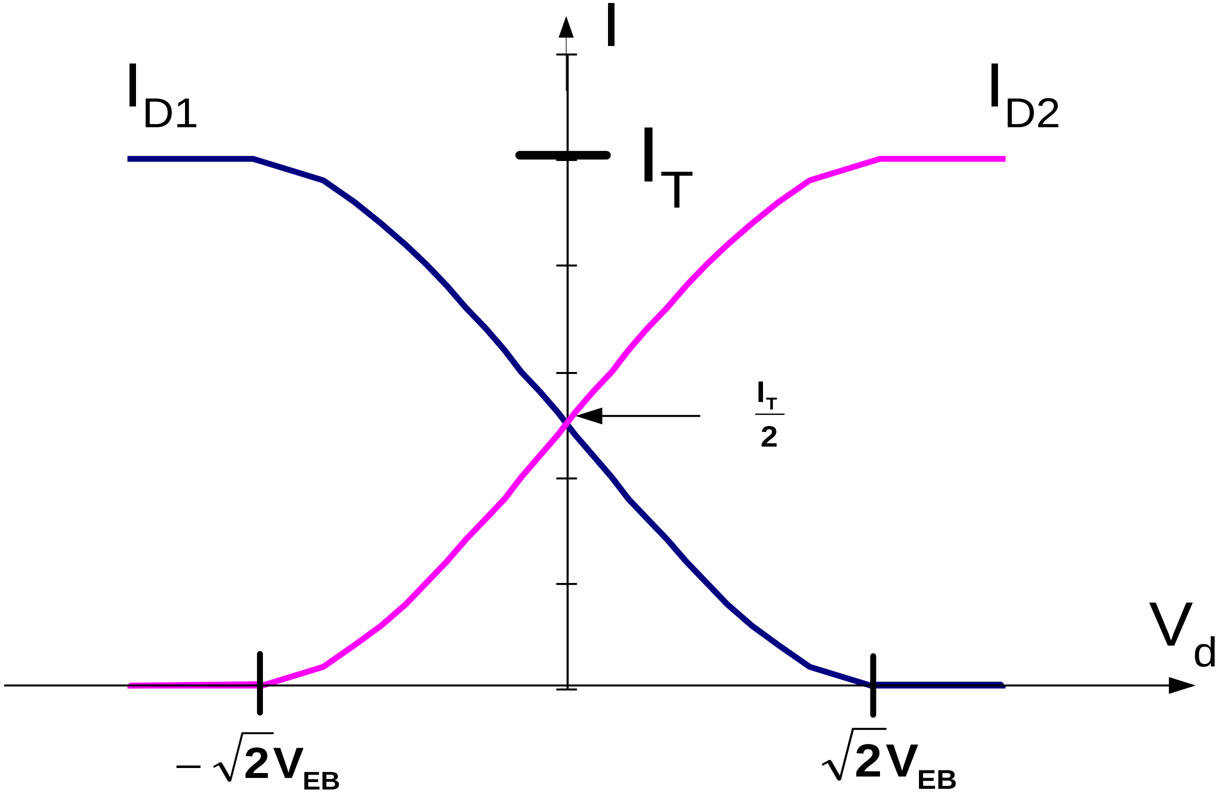
$$\frac{I_T}{2} = \frac{\mu C_{OX} W}{2L}\left(V_{EB}\right)^2$$

$$V_{EB} = \sqrt{I_T}\sqrt{\frac{L}{\mu C_{OX} W}}$$

Observe !!

$$V_{dx} = \pm\sqrt{2}V_{EB}$$

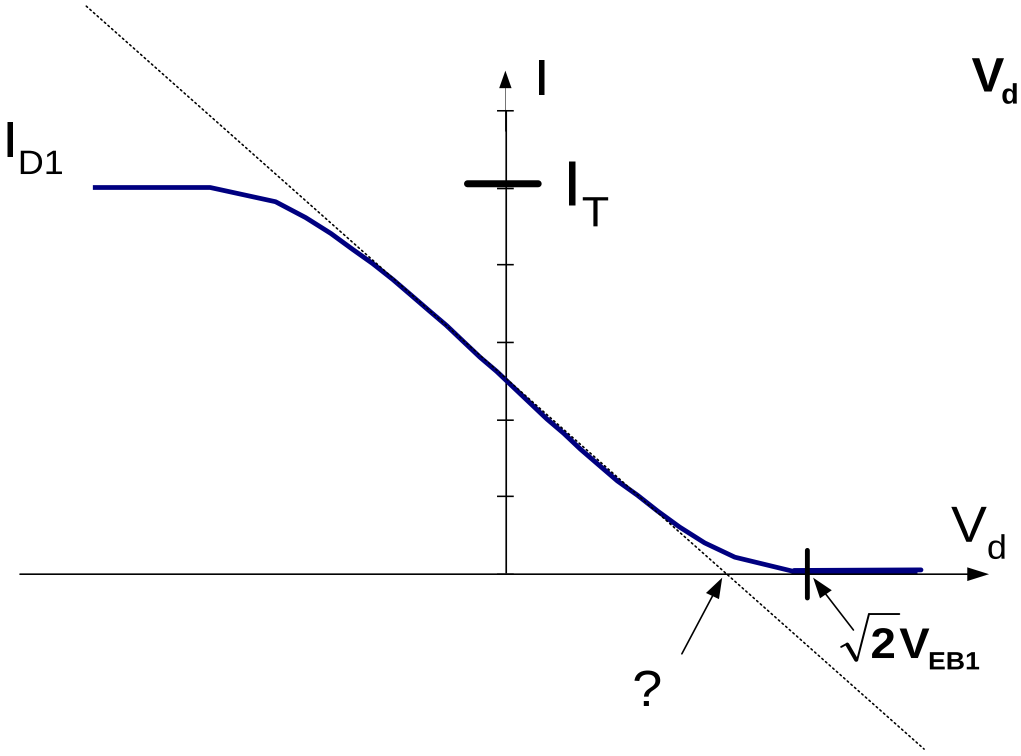
$$V_d = \sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_{D2}} - \sqrt{I_T - I_{D2}}\right)$$



V_{EB} affects linearity

How linear is the amplifier ?

How linear is the amplifier ?



$$V_d = \sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_T - I_{D1}} - \sqrt{I_{D1}}\right)$$

Consider the fit line:

$$I = mV_d + h$$

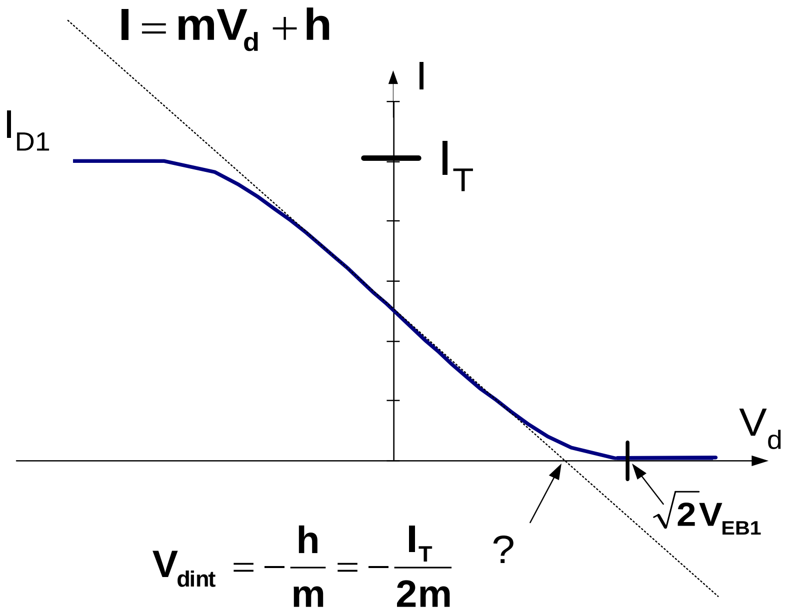
When V_d=0, I=I_T/2, thus

$$h = \frac{I_T}{2}$$

$$V_{dint} = -\frac{h}{m} = -\frac{I_T}{2m}$$

$$m = \left.\frac{\partial I_{D1}}{\partial V_d}\right|_{Q-pt}$$

How linear is the amplifier ?



$$I = mV_d + h$$

$$V_{dint} = -\frac{h}{m} = -\frac{I_T}{2m}$$

$$m = \left.\frac{\partial I_{D1}}{\partial V_d}\right|_{Q-pt}$$

$$V_d = \sqrt{\frac{2L}{\mu C_{OX} W}}\left(\sqrt{I_T - I_{D1}} - \sqrt{I_{D1}}\right)$$

$$\frac{\partial V_d}{\partial I_{D1}} = \sqrt{\frac{2L}{\mu C_{OX} W}}\left.\left(\frac{1}{2}(I_T - I_{D1})^{-1/2}(-1) - \frac{1}{2}(I_{D1})^{-1/2}\right)\right|_{Q-point}$$

$$\frac{\partial V_d}{\partial I_{D1}} = -2\sqrt{\frac{L}{\mu C_{OX} W}}\sqrt{\frac{1}{I_T}}$$

$$\sqrt{\frac{L}{\mu C_{OX} W}} = \frac{V_{EB1}}{\sqrt{I_T}}$$

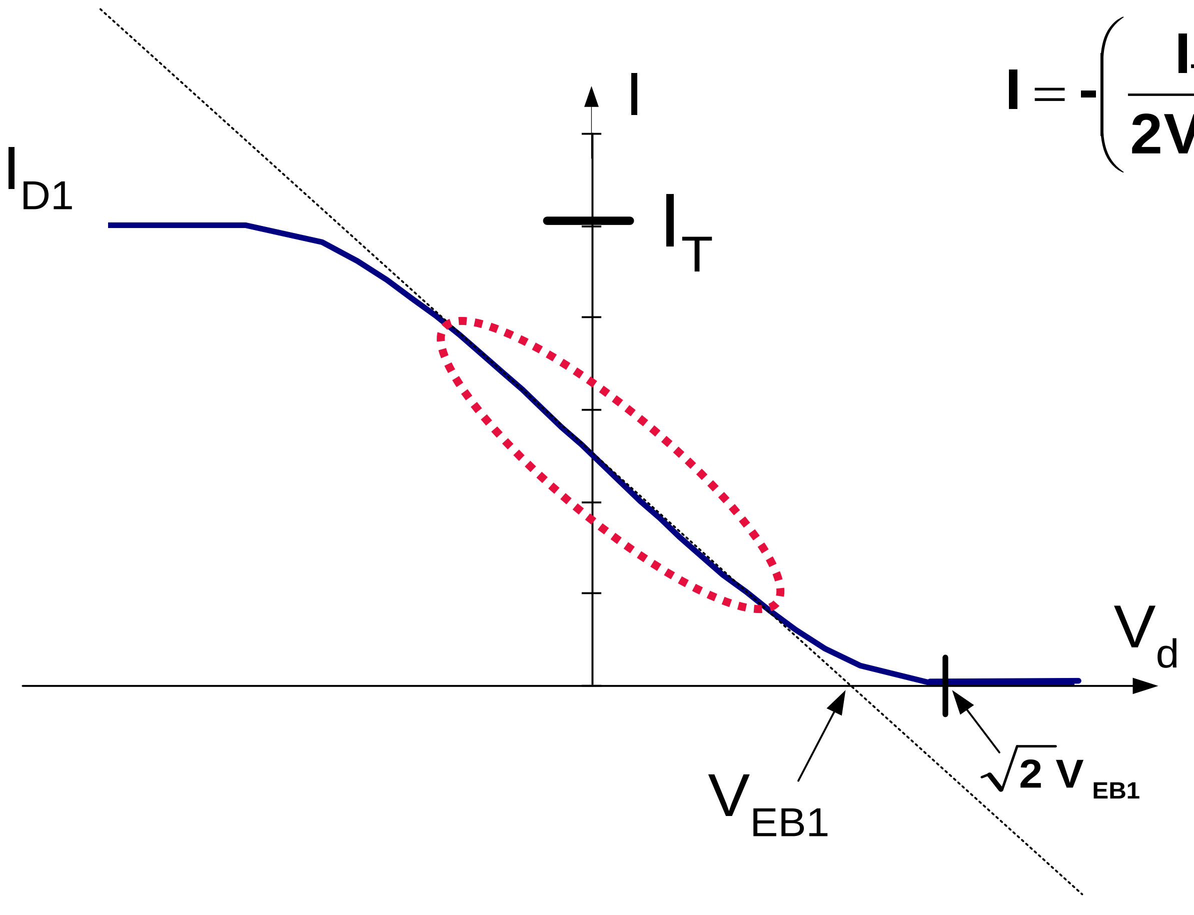
$$\frac{\partial V_d}{\partial I_{D1}} = -2\frac{V_{EB1}}{I_T}$$

$$m = \left.\frac{\partial I_{D1}}{\partial V_d}\right|_{Q-pt} = -\frac{I_T}{2V_{EB1}}$$

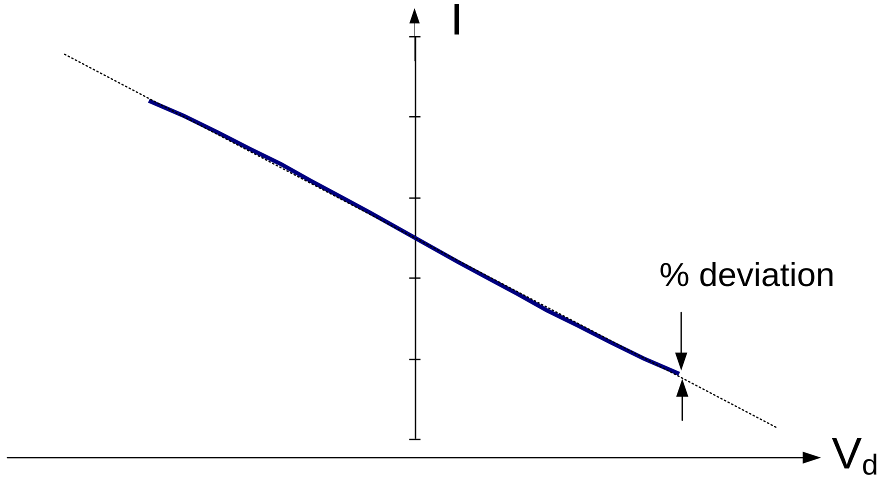
How linear is the amplifier ?

$$V_{dint} = -\frac{h}{m} = -\frac{I_T}{2m} = V_{EB1}$$

$$I = -\left(\frac{I_T}{2V_{EB1}}\right)V_d + \frac{I_T}{2}$$



How linear is the amplifier ?

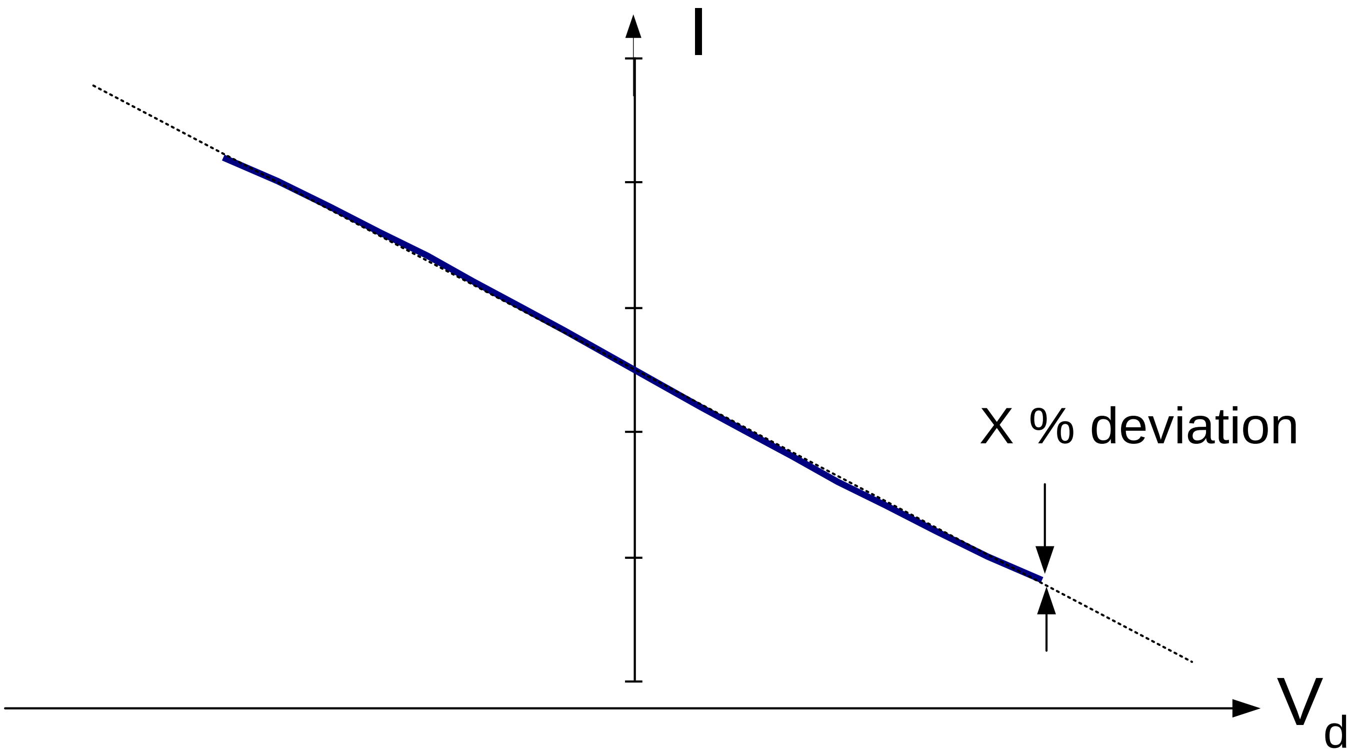


It can be shown that the deviation from the line in % is given by

$$\theta = 100\% \left(1 - \sqrt{1 - \frac{\left(V_d / V_{EB} \right)^2}{4}} \right)$$

Vd/VEB	θ	Vd/VEB	θ	Vd/VEB	θ
0.02	0.005	0.22	0.607	0.42	2.23
0.04	0.020	0.24	0.723	0.44	2.45
0.06	0.045	0.26	0.849	0.46	2.68
0.08	0.080	0.28	0.985	0.48	2.92
0.1	0.125	0.3	1.13	0.5	3.18
0.12	0.180	0.32	1.29	0.52	3.44
0.14	0.245	0.34	1.46	0.54	3.71
0.16	0.321	0.36	1.63	0.56	4.00
0.18	0.406	0.38	1.82	0.58	4.30
0.2	0.501	0.4	2.02	0.6	4.61

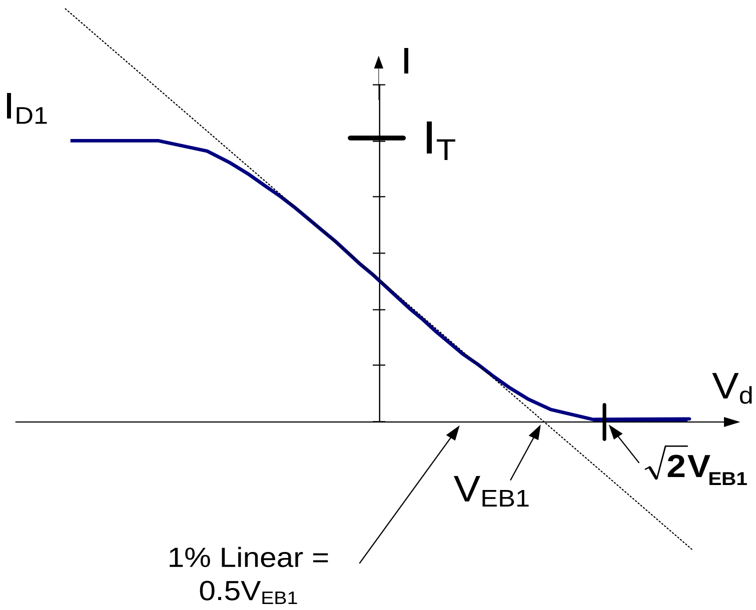
How linear is the amplifier ?



A 1% deviation from the straight line occurs at

$V_d \cong 0.3V_{EB}$ and a 0.1% variation occurs at $V_d \cong \frac{V_{EB}}{10}$

What swings on drain currents are typical when using the differential pair in an amplifier?



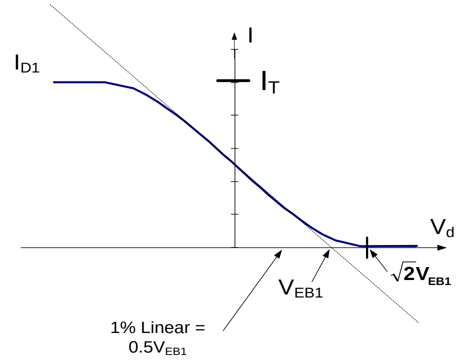
Assume the differential amplifier is the input stage to an op amp with gain Av and signal swing V_{OUTpp}

The differential swing at the input is thus

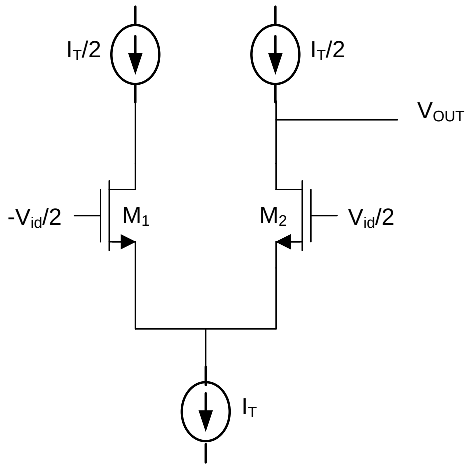
$$V_{INpp} = \frac{V_{OUTpp}}{A_V}$$

What swings on drain currents are typical when using the differential pair in an amplifier?

$$V_{INpp} = \frac{V_{OUTpp}}{A_V}$$



If the amplifier is the simple differential amplifier with current source loads



$$A_V = -\frac{g_{m1}}{2g_0} = \frac{2I_{DQ}/V_{EB1}}{2\lambda I_{DQ}}$$

$$A_V = -\frac{1}{\lambda V_{EB1}}$$

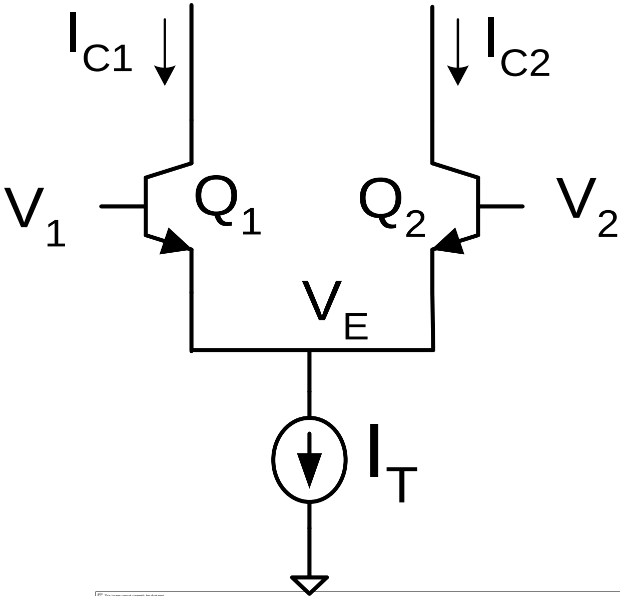
$$V_{INpp} = (\lambda V_{OUTpp})V_{EB1}$$

If $\lambda = .01V^{-1}$ and $V_{OUTpp} = 5V$,

$$V_{INpp} = 0.05V_{EB1}$$

This results in a very small nonlinearity and a very small change in current
When used in two-stage structure, even much smaller!

Bipolar Differential Pair



$$I_{C1} = J_S A_{E1} e^{\frac{V_1 - V_E}{V_t}}$$

$$I_{C2} = J_S A_{E2} e^{\frac{V_2 - V_E}{V_t}}$$

$$I_{C1} + I_{C2} = I_T$$

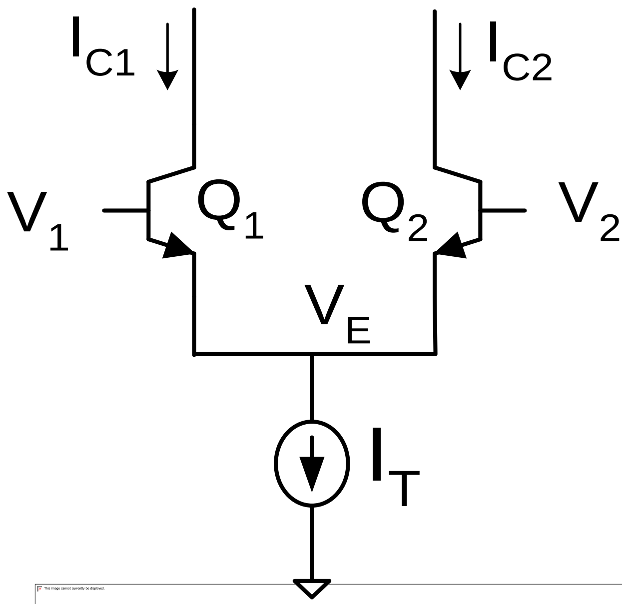
$$V_1 = V_E + V_t \ln\left(\frac{I_{C1}}{J_S A_{E1}}\right)$$

$$V_2 = V_E + V_t \ln\left(\frac{I_{C2}}{J_S A_{E2}}\right)$$

$$V_d = V_2 - V_1$$

$$V_d = V_t\left(\ln\left(\frac{I_{C2}}{J_S A_{E2}}\right) - \ln\left(\frac{I_{C1}}{J_S A_{E1}}\right)\right) \overset{A_{E1}=A_{E2}}{=} V_t \ln\left(\frac{I_{C2}}{I_{C1}}\right)$$

Bipolar Differential Pair



$$V_d = V_t\left(\ln\left(\frac{I_{C2}}{J_S A_{E2}}\right) - \ln\left(\frac{I_{C1}}{J_S A_{E1}}\right)\right) \overset{A_{E1}=A_{E2}}{=} V_t \ln\left(\frac{I_{C2}}{I_{C1}}\right)$$

$$V_d = V_2 - V_1$$

$$V_d = V_t \ln\left(\frac{I_T - I_{C1}}{I_{C1}}\right)$$

$$V_d = V_t \ln\left(\frac{I_{C2}}{I_T - I_{C2}}\right)$$

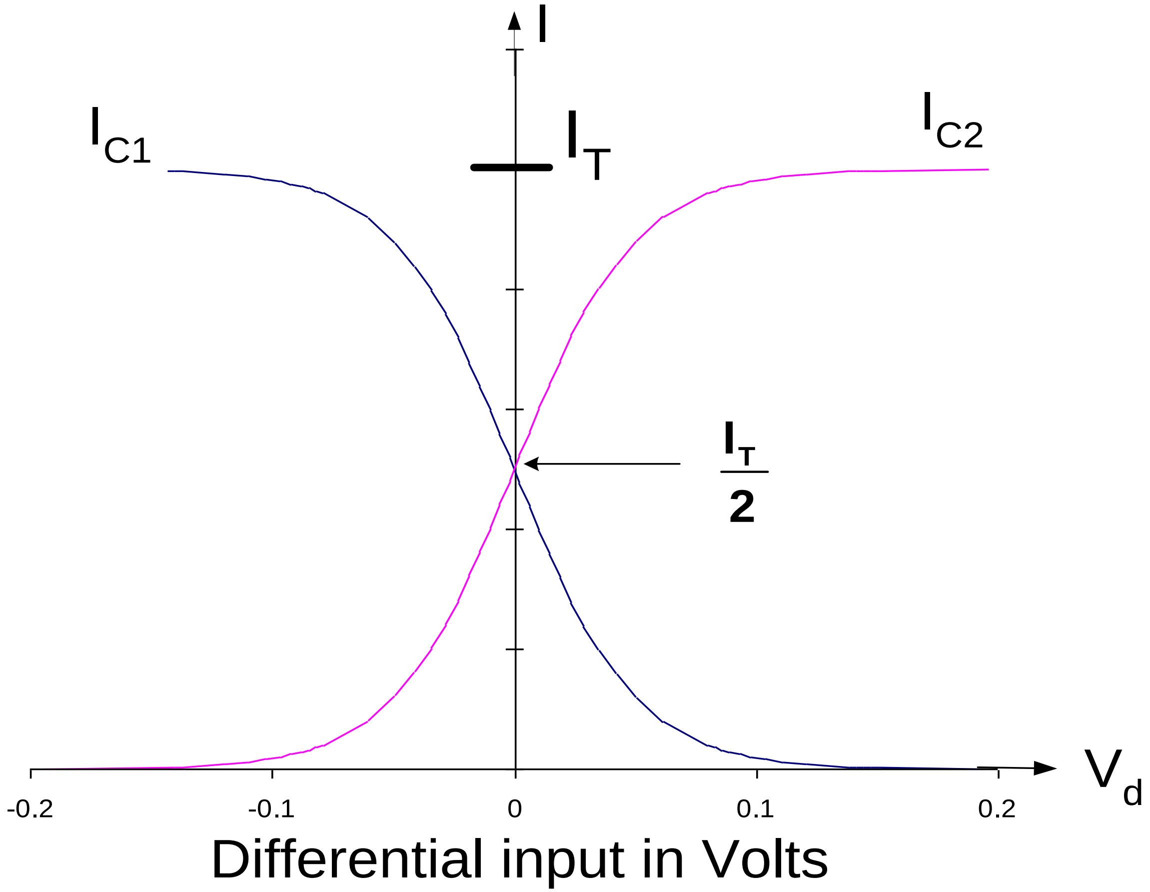
At $I_{C1}=I_{C2}=I_T/2$, $V_d=0$

As I_{C1} approaches 0, V_d approaches infinity

As I_{C1} approaches I_T, V_d approaches minus infinity

Transition much steeper than for MOS case

Transfer Characteristics of Bipolar Differential Pair

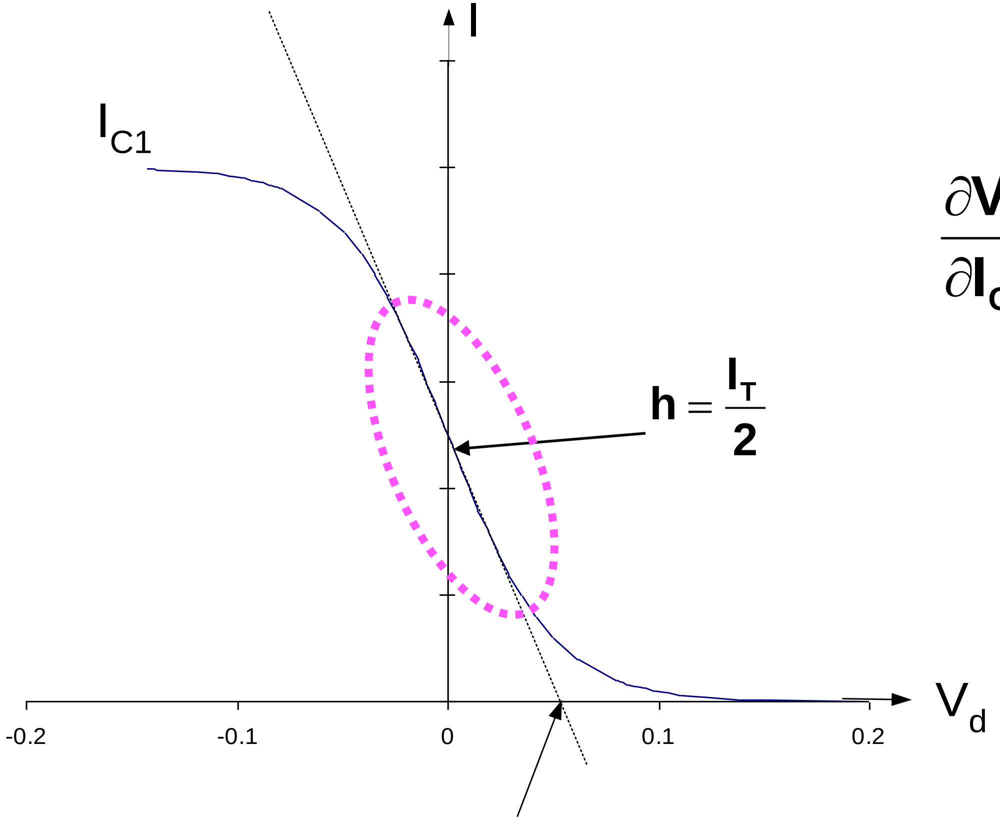


Transition much steeper than for MOS case

Asymptotic Convergence to 0 and I_T

Signal Swing and Linearity of Bipolar Differential Pair

$$I_{FIT} = mV_d + h$$



$$h = \frac{I_T}{2}$$

$$V_{dint} = -\frac{h}{m} = ?$$

$$m = \left.\frac{\partial I_{C1}}{\partial V_d}\right|_{Q-point}$$

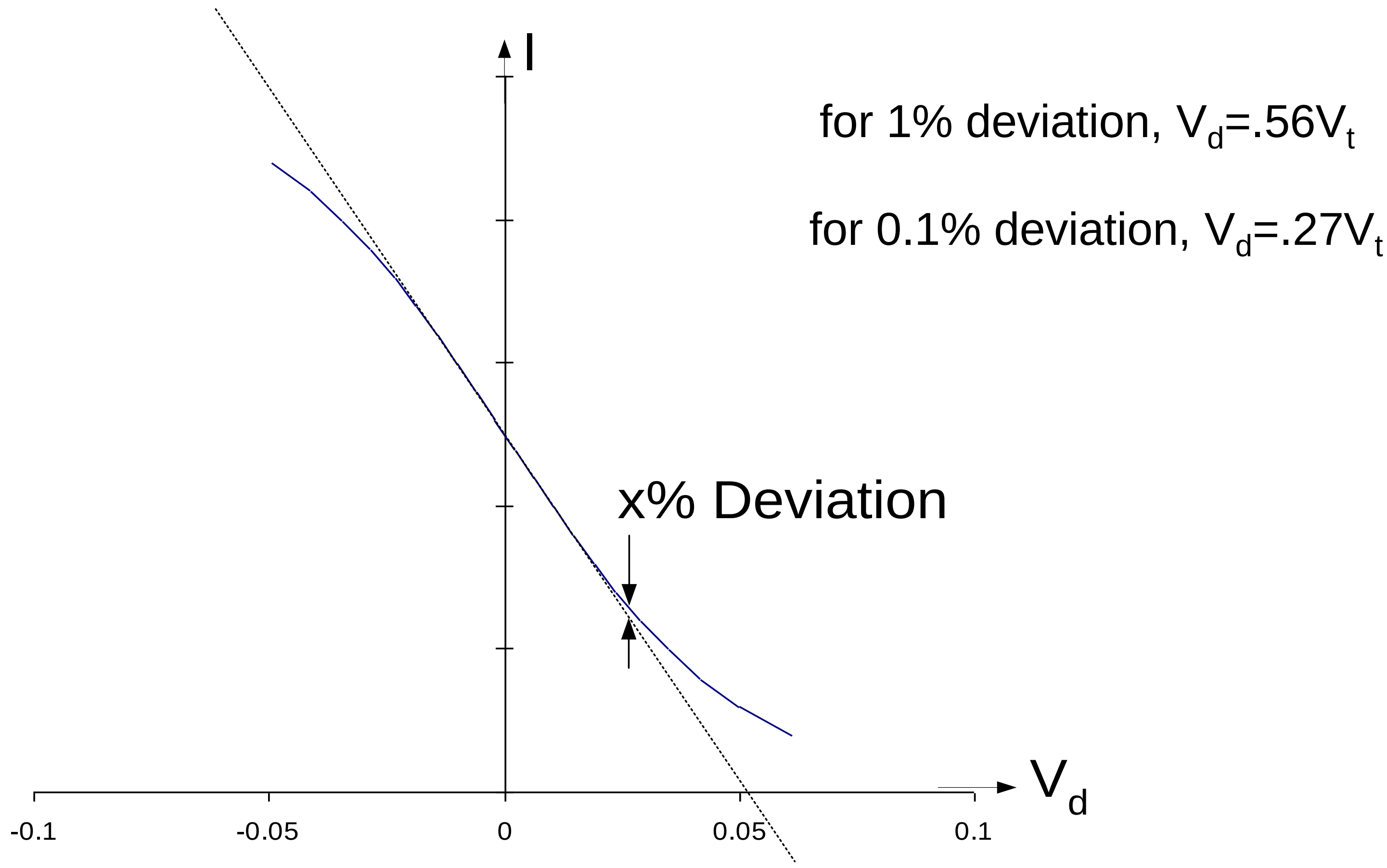
$$\left.\frac{\partial V_d}{\partial I_{C1}}\right|_{Q-point} = -V_t \left.\frac{I_T}{I_{C1}(I_T - I_{C1})}\right|_{I_{C1}=\frac{I_T}{2}}$$

$$\left.\frac{\partial V_d}{\partial I_{C1}}\right|_{Q-point} = -\frac{4V_t}{I_T}$$

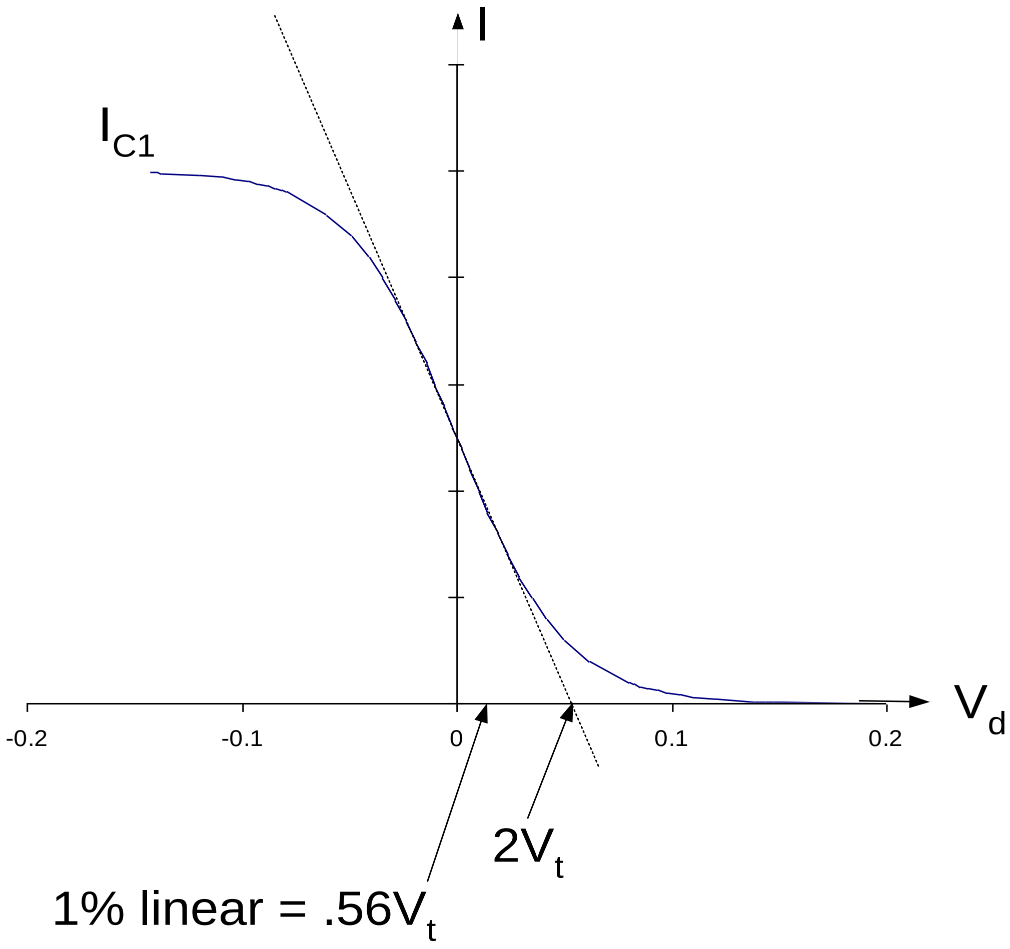
$$I_{FIT} = -\frac{I_T}{4V_t}V_d + \frac{I_T}{2}$$

$$V_{dint} = -\frac{h}{m} = 2V_t$$

Signal Swing and Linearity of Bipolar Differential Pair



Signal Swing and Linearity of Bipolar Differential Pair



Signal Swing and Linearity Summary

- Signal swing of MOSFET can be rather large if V_{EB} is large but this limits gain
- Signal swing of MOSFET degrades significantly if V_{EB} is changed for fixed W/L
- Bipolar swing is very small but independent of g_m
- Multiple-decade adjustment of bipolar g_m is practical
- Even though bipolar input swing is small, since gain is often very large, this small swing does usually not limit performance in feedback applications