EEE 51: Second Semester 2017 - 2018

Lecture 9

Differential Circuits

Today

- Differential Circuits

Differential Signals Revisited

- Limit analysis to sinusoids → easier analysis

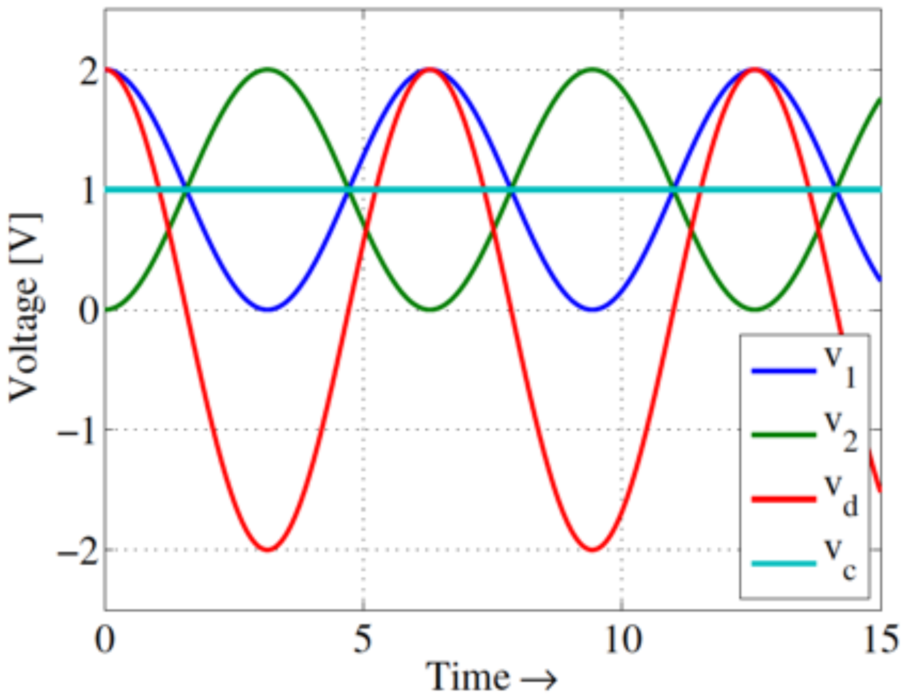
$$v_{i1} = \frac{\widehat{V}}{2}\cos(\omega t) + V_{cm}$$

$$v_{i2} = -\frac{\widehat{V}}{2}\cos(\omega t) + V_{cm}$$

$$v_{id} = v_{i1} - v_{i2} = \widehat{V}\cos(\omega t)$$

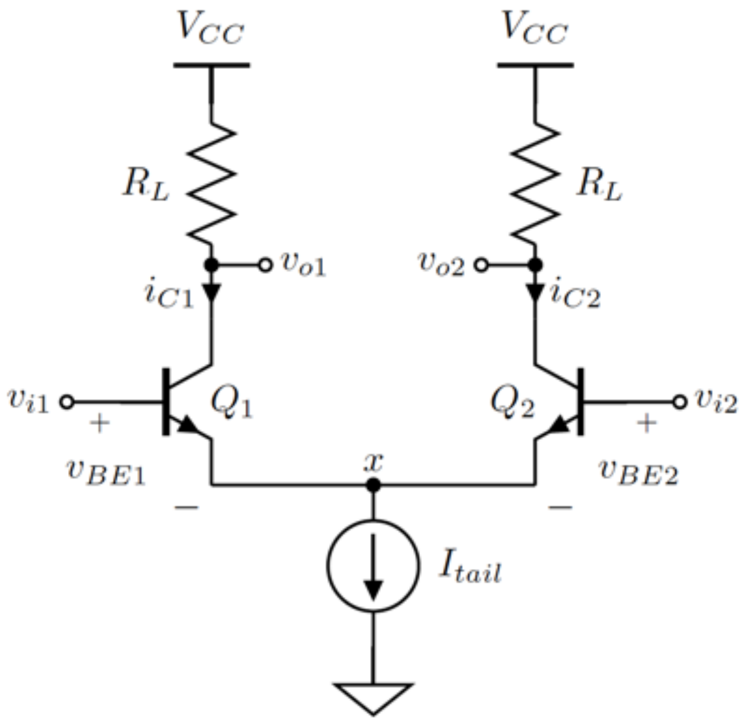
$$v_{ic} = \frac{v_{i1} + v_{i2}}{2} = V_{cm}$$

Common-mode ≈ DC Offset



Recall: The Differential Pair (1)

- BJT: The emitter-coupled pair DC Analysis



KVL at the input loop: $V_{i1} - V_{BE1} + V_{BE2} - V_{i2} = 0$

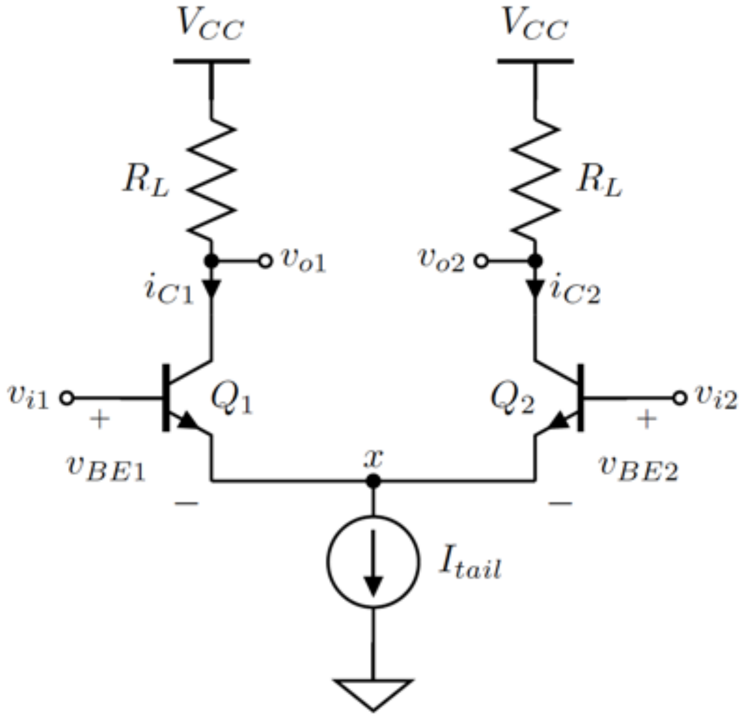
$$V_{i1} - V_{i2} = V_{BE1} - V_{BE2}$$

$$V_{id} = V_T \ln\left(\frac{I_{C1}}{I_S}\right) - V_T \ln\left(\frac{I_{C2}}{I_S}\right) = V_T \ln\left(\frac{I_{C1}}{I_{C2}}\right)$$

$$\boxed{I_{C1} = I_{C2} \cdot e^{\frac{V_{id}}{V_T}}}$$

Recall: The Differential Pair (2)

- BJT: The emitter-coupled pair DC Analysis



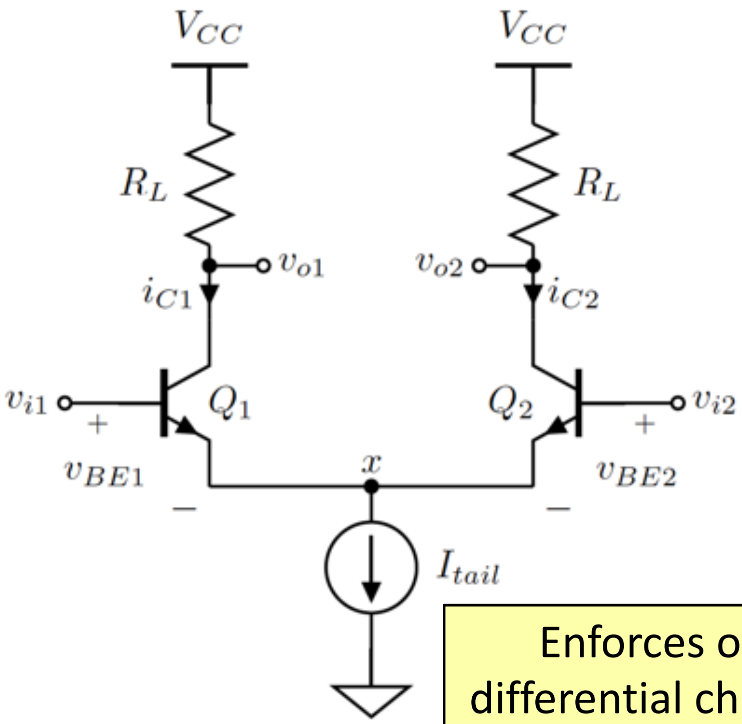
KCL at node x: $$I_{tail} = I_{E1} + I_{E2} = \frac{I_{C1} + I_{C2}}{\alpha}$$

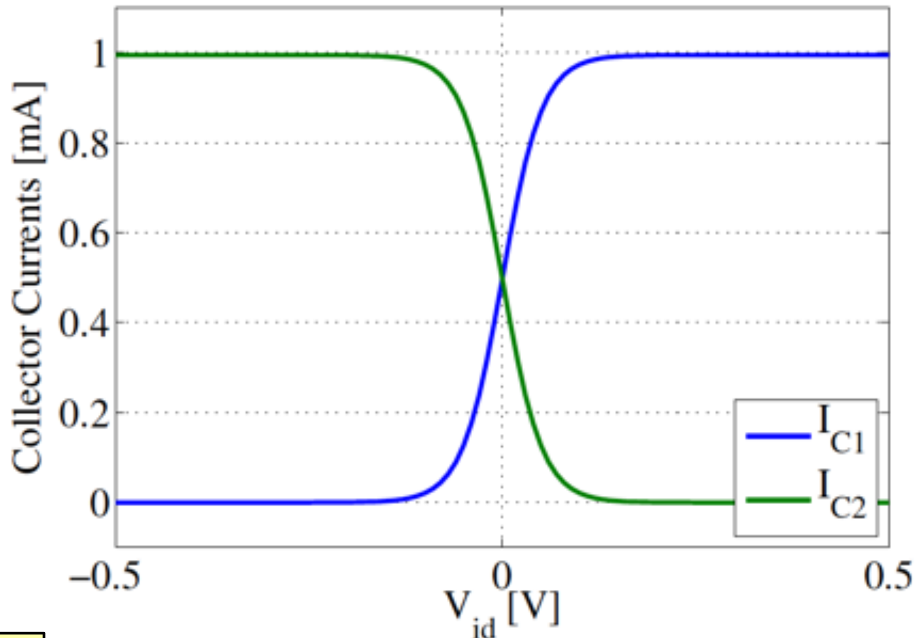
Recall: $$\boxed{I_{C1} = I_{C2} \cdot e^{\frac{V_{id}}{V_T}}}$$

$$\boxed{I_{C1} = \frac{\alpha \cdot I_{tail}}{1 + e^{-\frac{V_{id}}{V_T}}}} \qquad \boxed{I_{C2} = \frac{\alpha \cdot I_{tail}}{1 + e^{+\frac{V_{id}}{V_T}}}}$$

Recall: The Differential Pair (3)

- BJT: The emitter-coupled pair DC Analysis





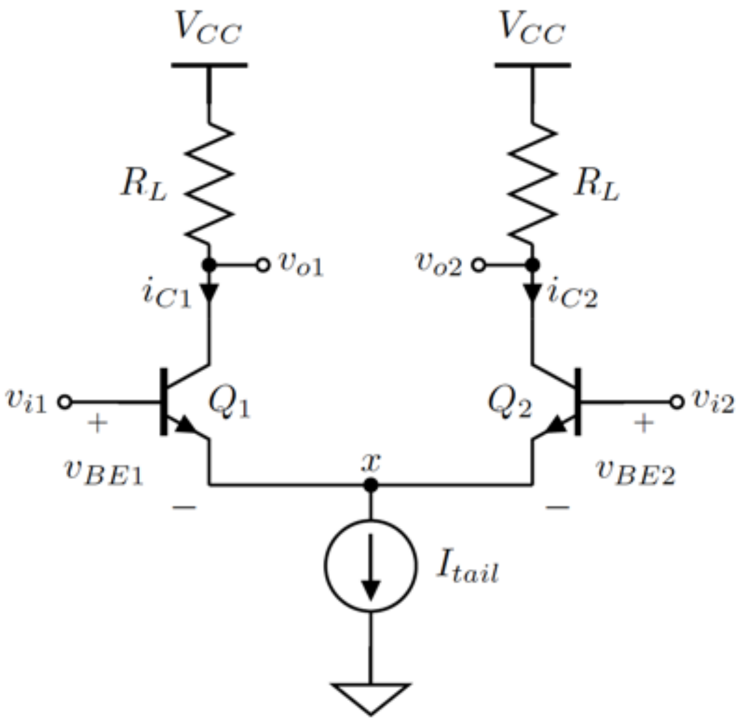
Enforces only differential changes!

$$I_{C1} = \frac{\alpha \cdot I_{tail}}{1 + e^{-\frac{V_{id}}{V_T}}}$$

$$I_{C2} = \frac{\alpha \cdot I_{tail}}{1 + e^{+\frac{V_{id}}{V_T}}}$$

Recall: The Differential Pair (4)

- Output Voltage



$$I_{C1} = \frac{\alpha \cdot I_{tail}}{1 + e^{-\frac{V_{id}}{V_T}}}$$

$$I_{C2} = \frac{\alpha \cdot I_{tail}}{1 + e^{+\frac{V_{id}}{V_T}}}$$

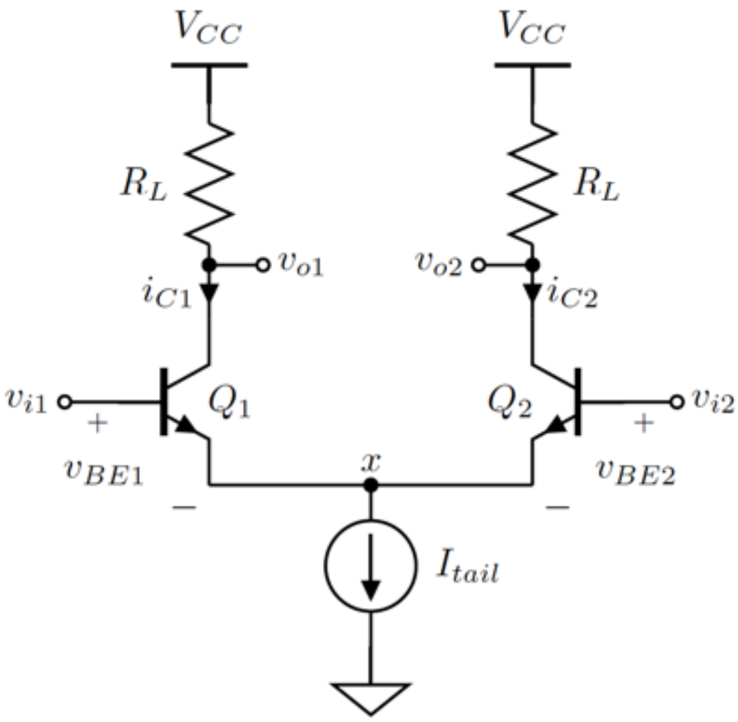
KVL at the output loop: $V_{od} = V_{o1} - V_{o2} = R_L\left(I_{C2} - I_{C1}\right)$

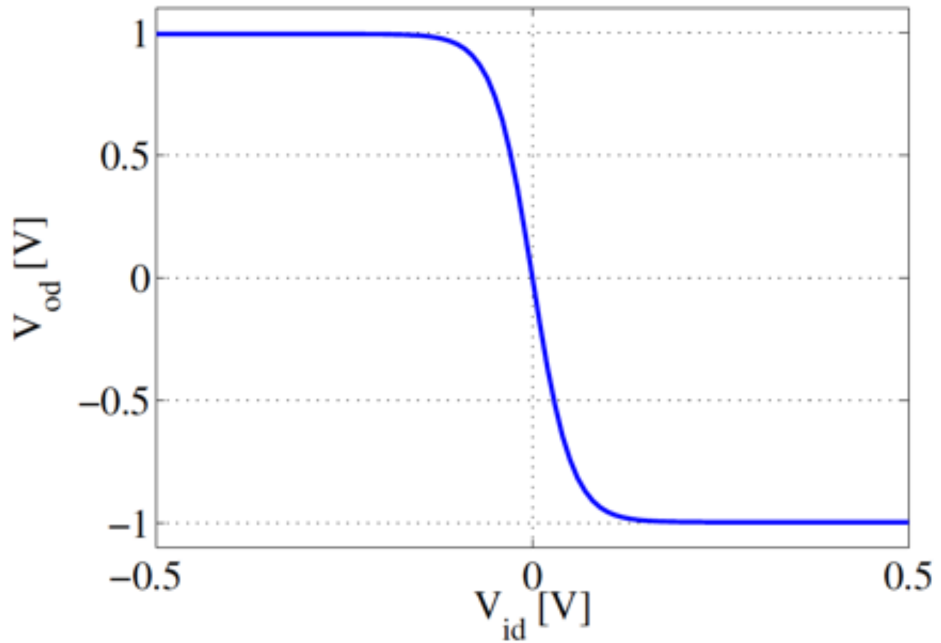
$$V_{od} = \alpha \cdot I_{tail} \cdot R_L \cdot \left(\frac{1}{1 + e^{+\frac{V_{id}}{V_T}}} - \frac{1}{1 + e^{-\frac{V_{id}}{V_T}}} \right)$$

$$= \alpha \cdot I_{tail} \cdot R_L \cdot \tanh\left(-\frac{V_{id}}{2 \cdot V_T} \right)$$

Recall: The Differential Pair (5)

- Transfer Characteristic

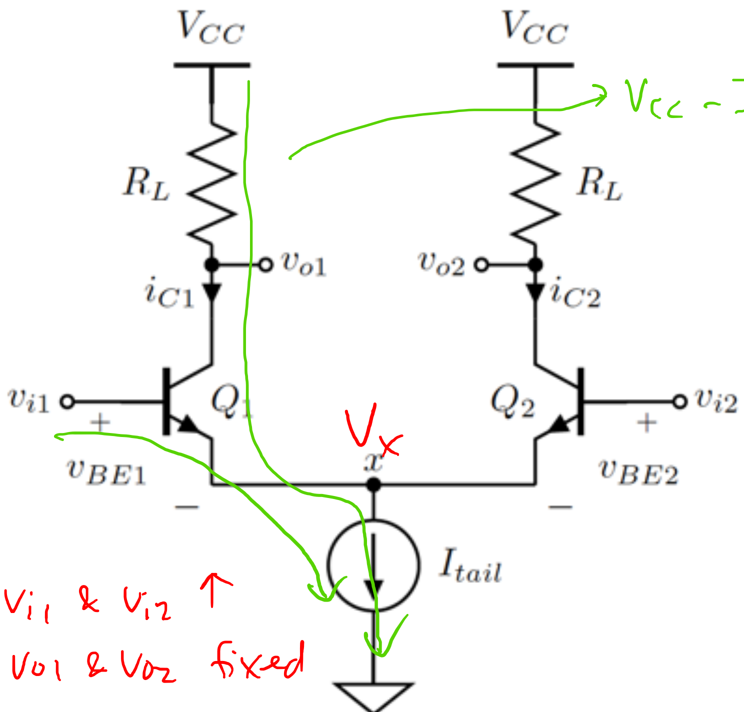




$$V_{od} = \alpha \cdot I_{tail} \cdot R_L \cdot \tanh\left(-\frac{V_{id}}{2 \cdot V_T}\right)$$

Common-Mode Input Range (1)

- BJT Operating Region?



$V_{CC} - I_{C1}R_L - V_{CE1} - V_x = \emptyset$

Assume zero differential input → $V_{i1} = V_{i2}$

KVL: $V_{CE1} = V_{CC} - I_{C1}R_L - V_X > V_{CE,sat}$

↑ to keep Q_1 in f.a.

Note: $V_X = V_{I1} - V_{BE1}$

$= V_{I1} - V_T \ln\left(\dfrac{I_{C1}}{I_S}\right)$

V_X is controlled by the input common-mode (DC input)!

as V_{i1} & V_{i2} ↑

V_{o1} & V_{o2} fixed

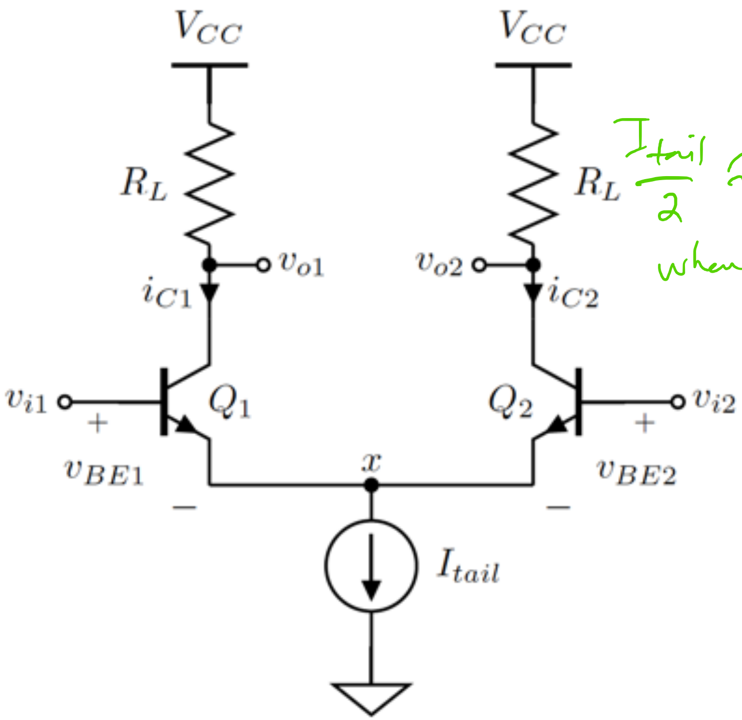
V_x ↑

$V_{CE1} = V_{o1} - V_x$, $V_{CE2} = V_{o2} - V_x$

$$V_{CE1} = V_{CC} - I_{C1}R_L - V_{I1} + V_T \ln\left(\frac{I_{C1}}{I_S}\right) > V_{CE1,sat}$$

Common-Mode Input Range (2)

- BJT Operating Region?



For zero differential input: $v_{ic} = V_{I1} = V_{I2} = V_{cm}$

$\frac{I_{tail}}{2} \approx$ $\boxed{I_{C1} = I_{C2} = \frac{\alpha I_{tail}}{2}}$ ⟸ For a range of common-mode inputs!

when β is large

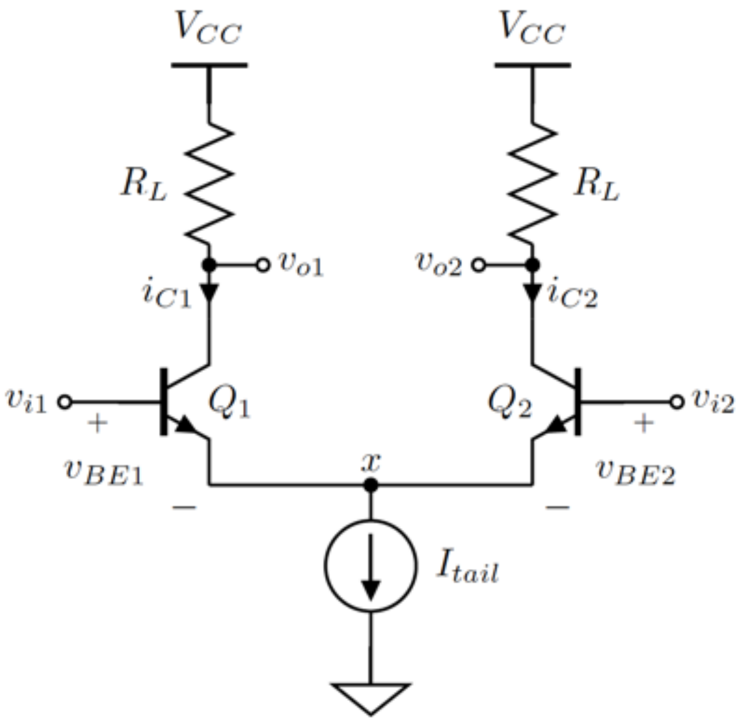
$$V_{CE1} = V_{CC} - I_{C1}R_L - V_{I1} + V_T \ln\left(\frac{I_{C1}}{I_S}\right)$$

I_{C1}: $\frac{I_{tail}}{2}$; V_{I1}: V_{cm} ; I_{C1}: $I_{tail}/2$

$$\boxed{V_{CE1} = V_{CC} - \frac{I_{tail}R_L}{2} - V_{cm} + V_T \ln\left(\frac{I_{tail}}{2 \cdot I_S}\right) > V_{CE,sat}}$$

Common-Mode Input Range (3)

- BJT Operating Region?



$$V_{CE1} = V_{CC} - \frac{I_{tail} R_L}{2} - V_{cm} + V_T \ln\left(\frac{I_{tail}}{2 \cdot I_S}\right) > V_{CE,sat}$$

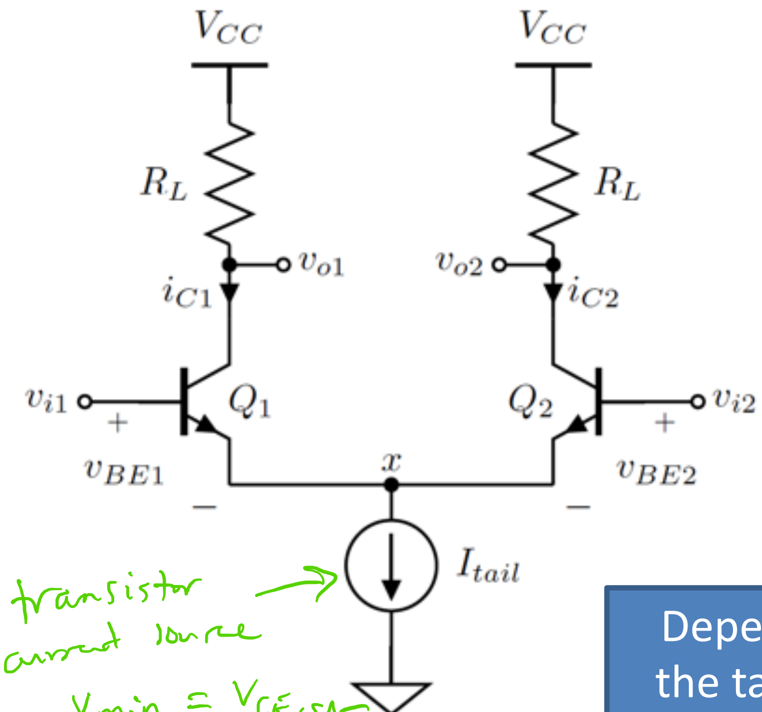
$$V_{cm} < V_{CC} - \frac{I_{tail} R_L}{2} + V_T \ln\left(\frac{I_{tail}}{2 \cdot I_S}\right) - V_{CE,sat}$$

Maximum common-mode input voltage:

$$\boxed{V_{cm,\max} = V_{CC} - \frac{I_{tail} R_L}{2} + V_T \ln\left(\frac{I_{tail}}{2 \cdot I_S}\right) - V_{CE,sat}}$$

Common-Mode Input Range (4)

- BJT Operating Region?



transistor current source

$V_{min} = V_{CE,SAT}$

If the tail current is not ideal → V_{min}

$$V_X = V_{I1} - V_{BE1}$$

I_{C1}

$$= V_{I1} - V_T \ln\left(\frac{I_{C1}}{I_S}\right) = V_{cm} - V_T \ln\left(\frac{I_{tail}}{2 \cdot I_S}\right) > V_{min}$$

$$V_{cm} > V_{min} + V_T \ln\left(\frac{I_{tail}}{2 \cdot I_S}\right)$$

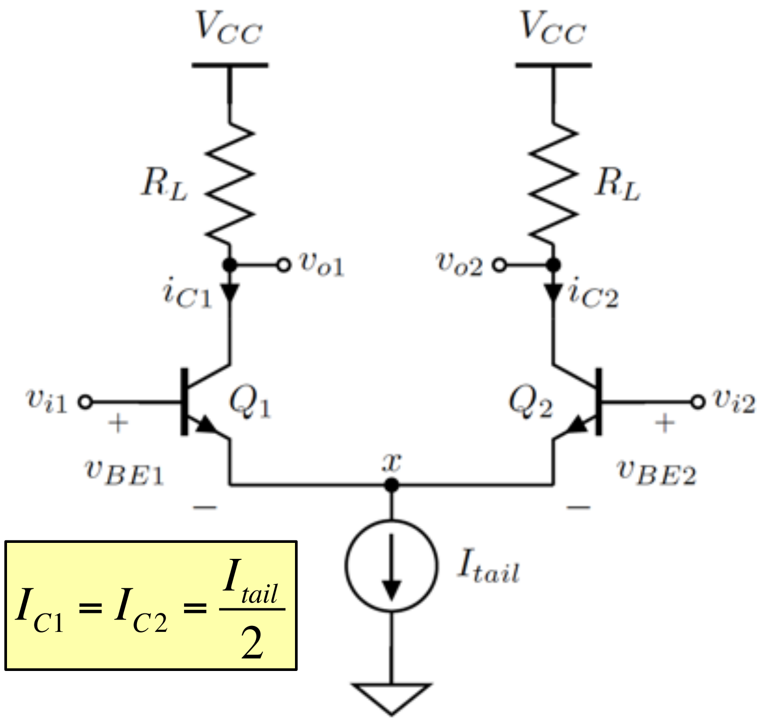
Minimum common-mode input voltage:

Dependent on the tail current source

$$\boxed{V_{cm,\min} = V_{\min} + V_T \ln\left(\frac{I_{tail}}{2 \cdot I_S}\right)}$$

Common-Mode Input Range (5)

- BJT Operating Region → set by the input common-mode!



$$I_{C1} = I_{C2} = \frac{I_{tail}}{2}$$

$$V_{cm,\max} = V_{CC} - \frac{I_{tail}R_L}{2} + V_T \ln\left(\frac{I_{tail}}{2 \cdot I_S}\right) - V_{CE,sat}$$

Common-mode input range

$$V_{cm,\min} = V_{\min} + V_T \ln\left(\frac{I_{tail}}{2 \cdot I_S}\right)$$

Next Meeting

- Continue with Differential Circuits