UNIVERSITY OF OSLO

MES
Mikro Elektroniske Systemer

Neuromorphic Electronics

Basic Analog CMOS

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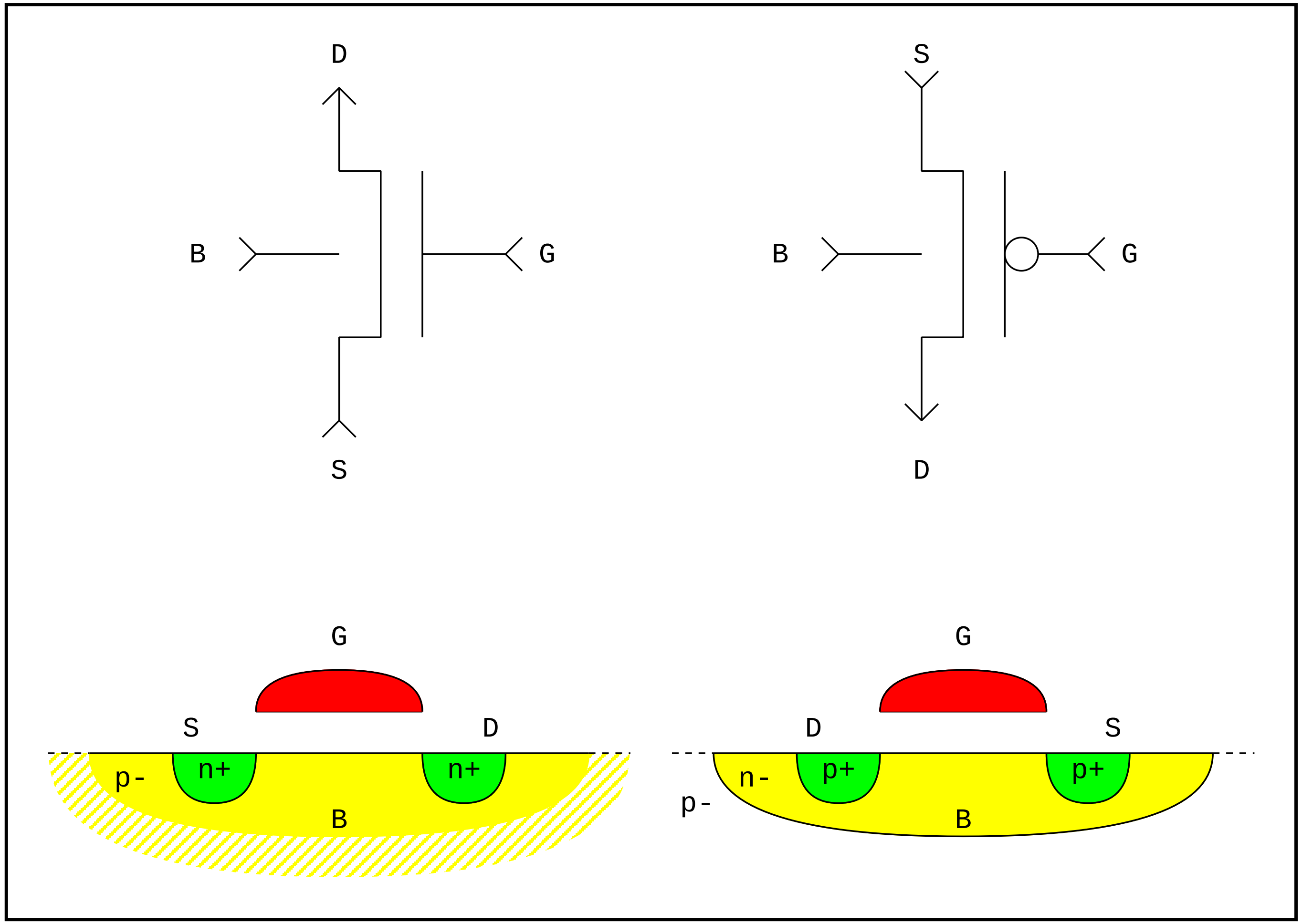
NFET symbol and cross section



NFET formulae (1/2)

$$I_{DS} = I_F - I_R$$

$$I_{F(R)} = I_S ln^2 \left[1 + e^{\frac{V_G - V_{T0} - nV_{S(D)}}{2nU_T}} \right]$$

$I_F >> I_R$: in saturation, else: triode region/linear region.

NFET formulae (2/2)

$I_F << I_S$ $(V_G < V_{T0} + nV_S)$: weak inversion/subthreshold

simplifies to: $I_F = I_S e^{\frac{V_G - V_{T0} - nV_S}{nU_T}}$

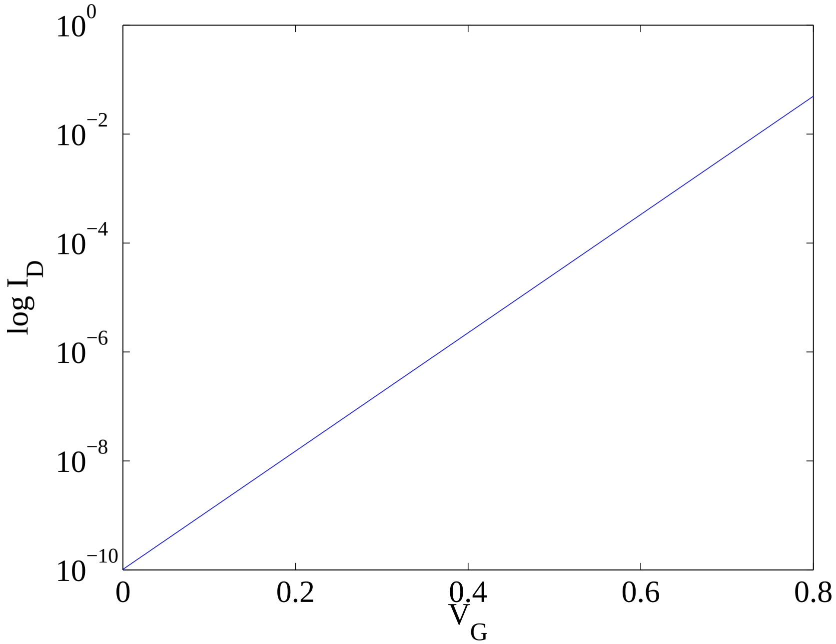
$I_F >> I_S$ $(V_G > V_{T0} + nV_S)$: strong inversion/above threshold

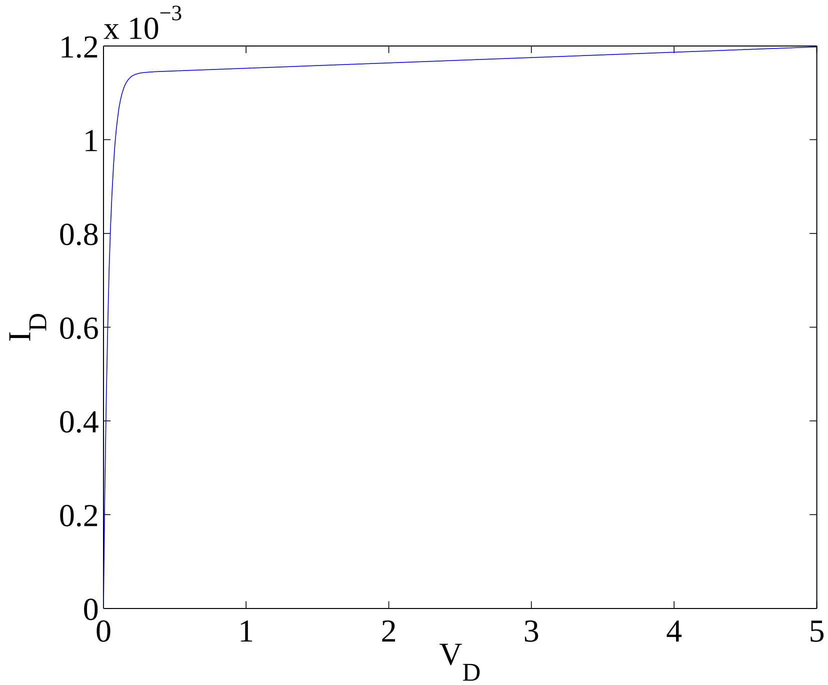
simplifies to: $I_{F(R)} = \frac{I_S}{4}\left(\frac{V_G - V_{T0} - nV_{S(D)}}{nU_T}\right)^2$

NFET Early effect

$$I_F = \frac{V_D + V_{Early}}{V_{Early}} I_F$$

NFET characteristics



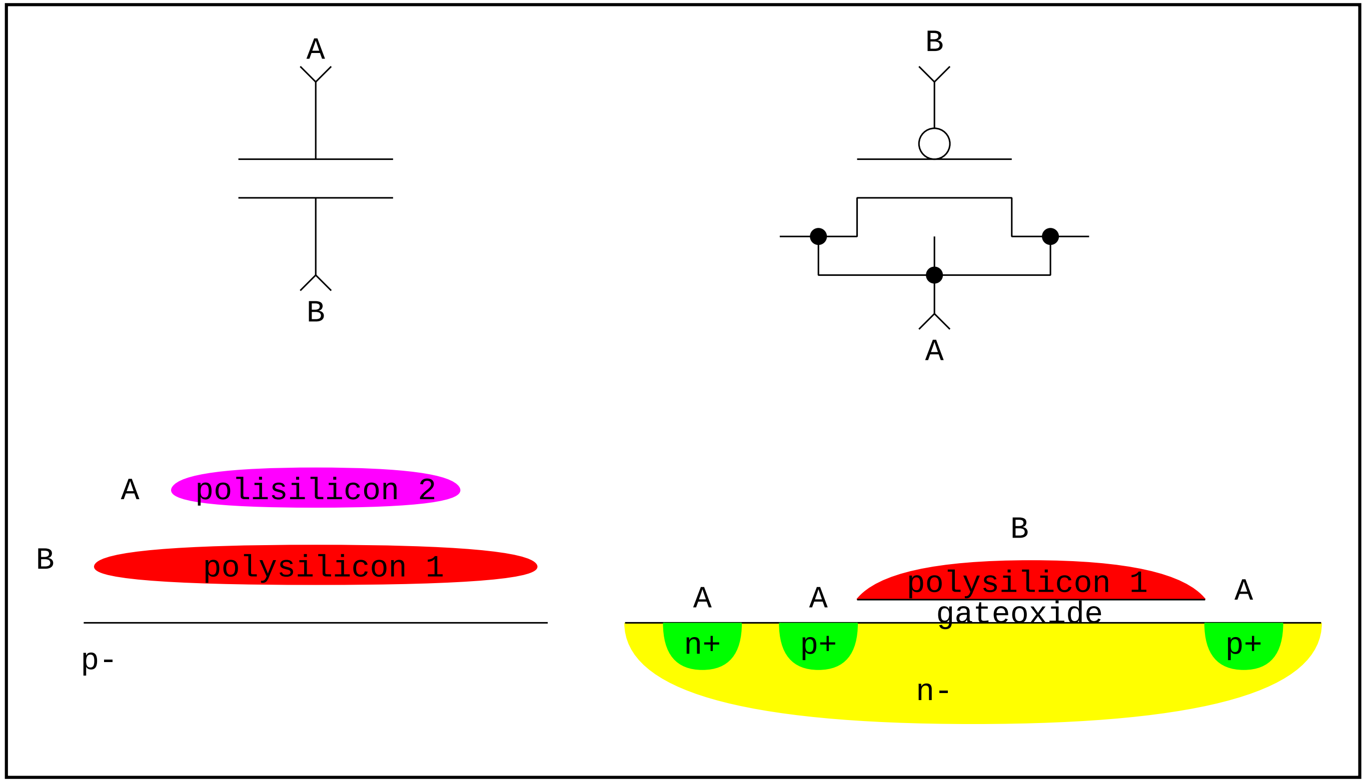


Briefly Mentioned: Gate Leakeage/Direct Tunneling

$t_{ox} \leq 2 - 3\text{nm}$

$$J_g = \begin{cases} A\frac{V_{ox}^2}{t_{ox}^2} e^{-\frac{B\left(1-\left(1-\frac{V_{ox} q_e}{\phi_{ox}}\right)^{\frac{2}{3}}\right)}{\frac{V_{ox}}{t_{ox}}}} & \text{if } V_{ox} < \frac{\phi_{ox}}{q_e} \\ A\frac{V_{ox}^2}{t_{ox}^2} e^{-\frac{B}{\frac{V_{ox}}{t_{ox}}}} & \text{if } V_{ox} < \frac{\phi_{ox}}{q_e} \end{cases} \quad (1)$$

Capacitor symbol and cross section

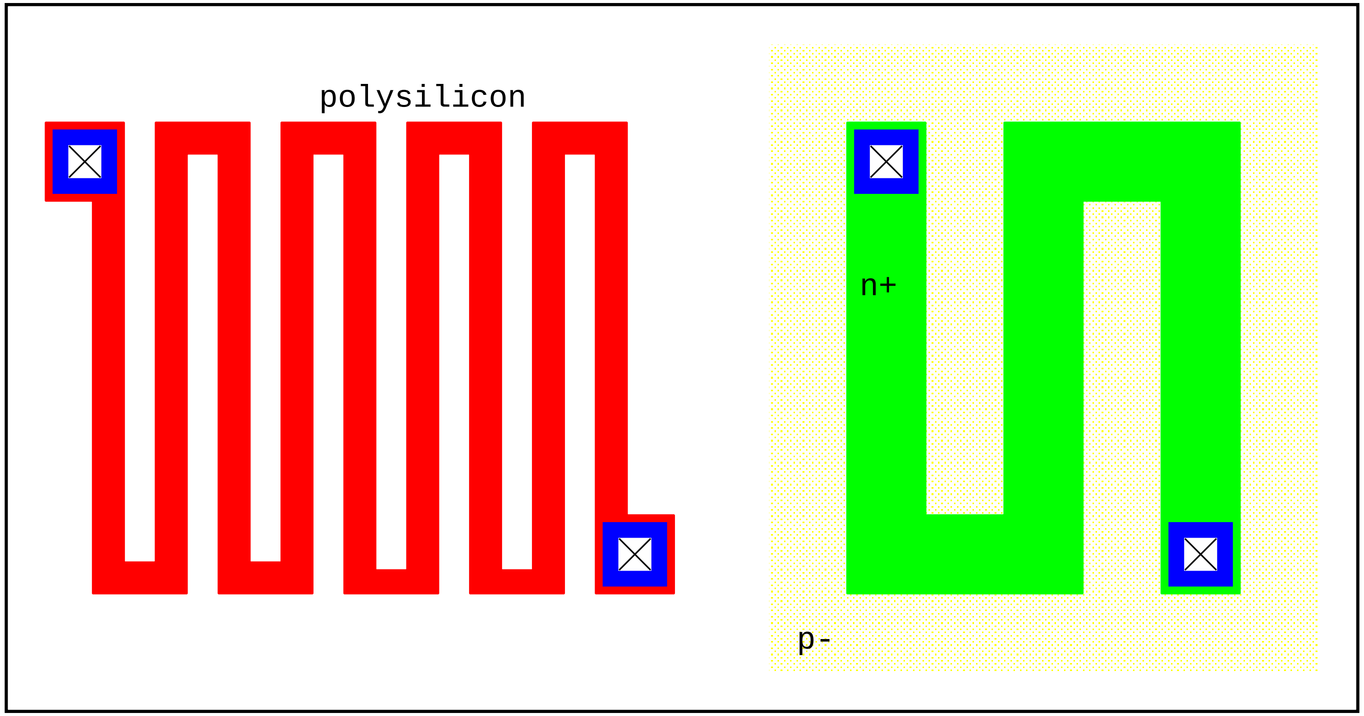


Capacitor formulae

$$V = \frac{1}{C}Q$$

$$\frac{\delta V}{\delta t} = \frac{1}{C}I$$

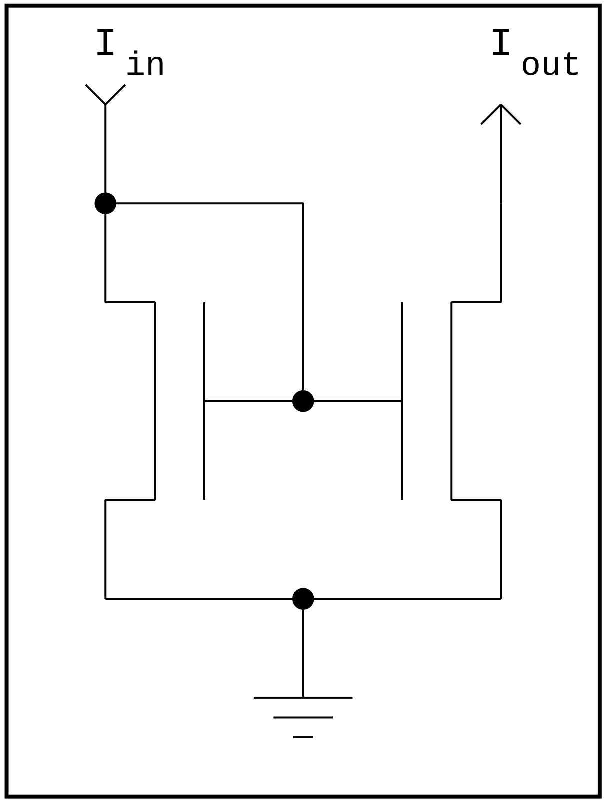
Resistor layout



Resistor formulae

$$V = RI$$

Current Mirror Schematics



Current Mirror formulae

$I_{out} = I_{in}$ (if both transistors are in saturation, and have the same W/L ratio, and neglecting the Early effect)

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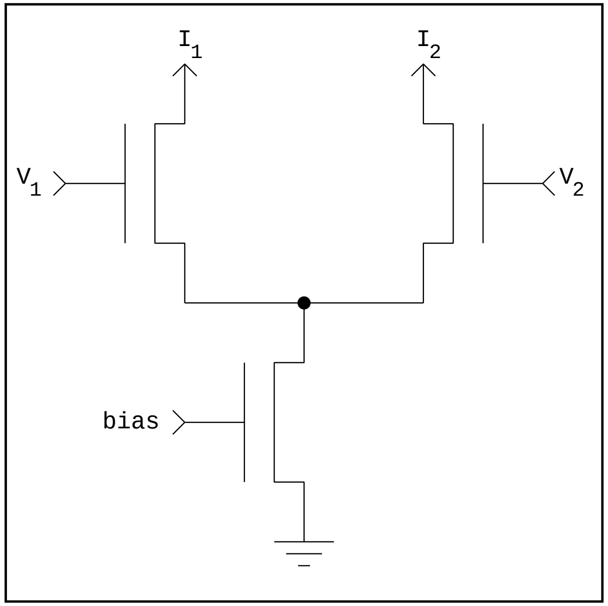
Differential Pair Schematics

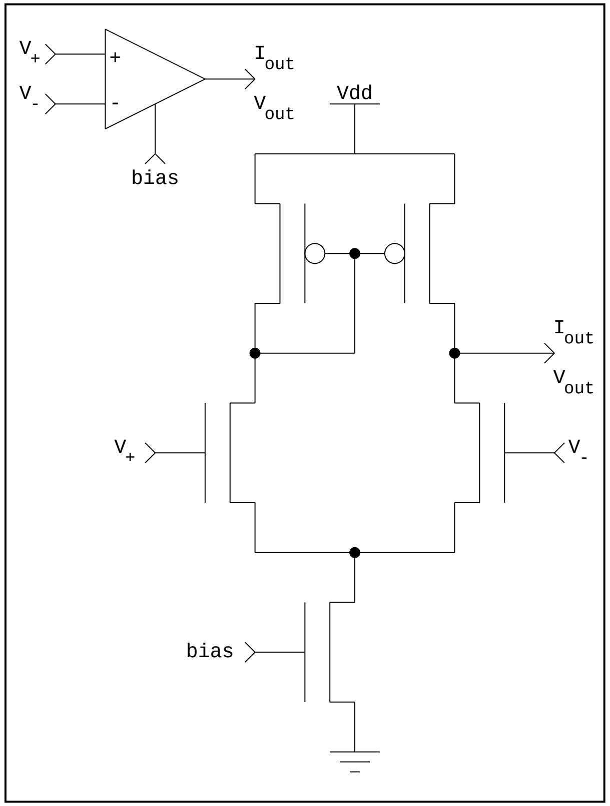


Differential Pair Formulae

$$I_b = I_1 + I_2 = I_S e^{\frac{-V_{T0}-V_C}{nU_T}} \left(e^{\frac{V_1}{nU_T}} + e^{\frac{V_2}{nU_T}} \right)$$

$$\frac{I_1}{I_2} = \frac{I_1}{I_b - I_1} = e^{\frac{V_1 - V_2}{nU_T}}$$

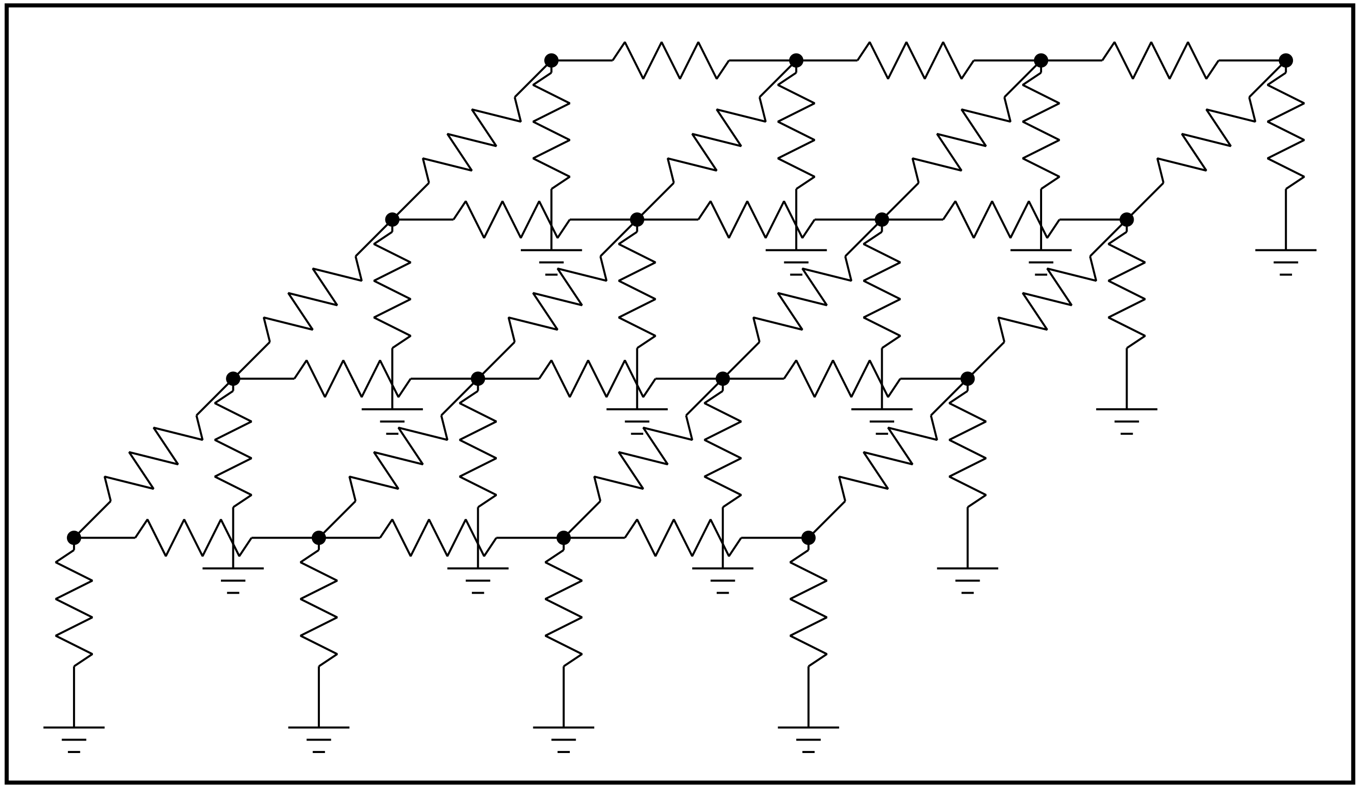
Transconductance Amplifier Schematics



Transconductance Amplifier Formulae

$$I_{out} = I_b \frac{e^{\frac{V_+}{nU_T}} - e^{\frac{V_-}{nU_T}}}{e^{\frac{V_+}{nU_T}} + e^{\frac{V_-}{nU_T}}} = I_b \tanh \frac{V_+ - V_-}{2nU_T}$$

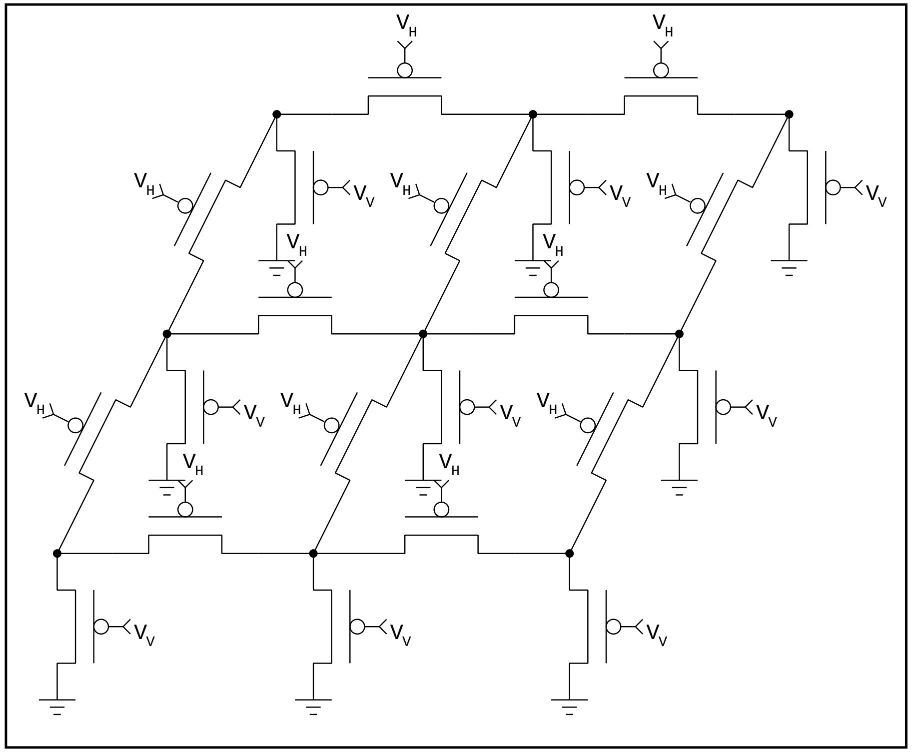
Resistive Net



Resistive Net Formulae

$$\frac{V}{R_V} = \frac{\delta^2}{\delta x^2 \delta y^2} \frac{V}{R_H}$$

Diffuser Net

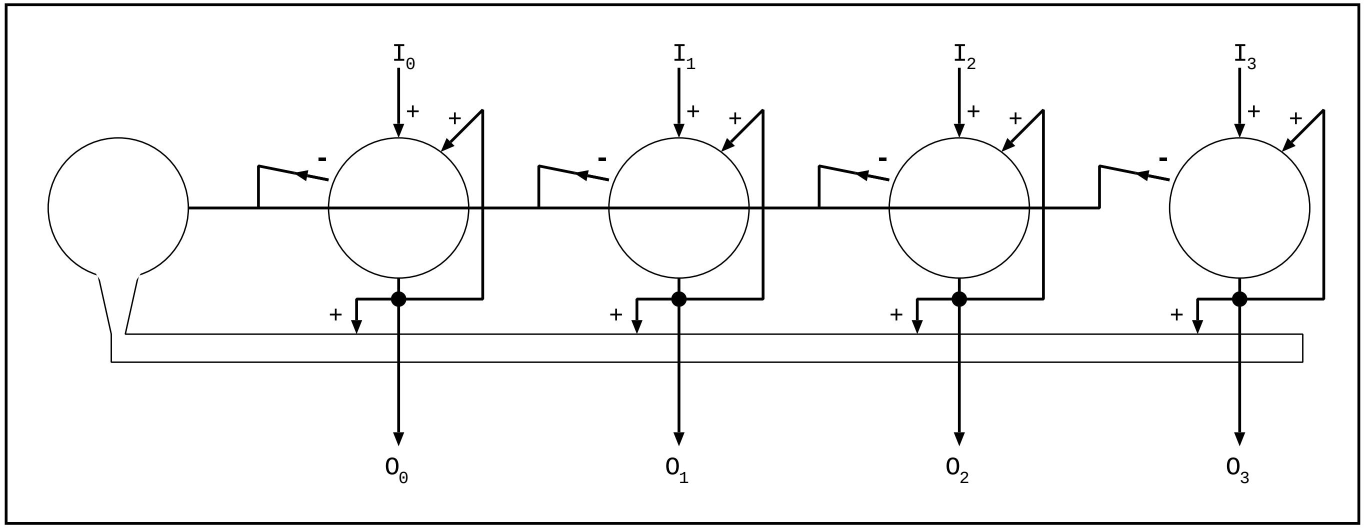


Diffuser Net Formulae

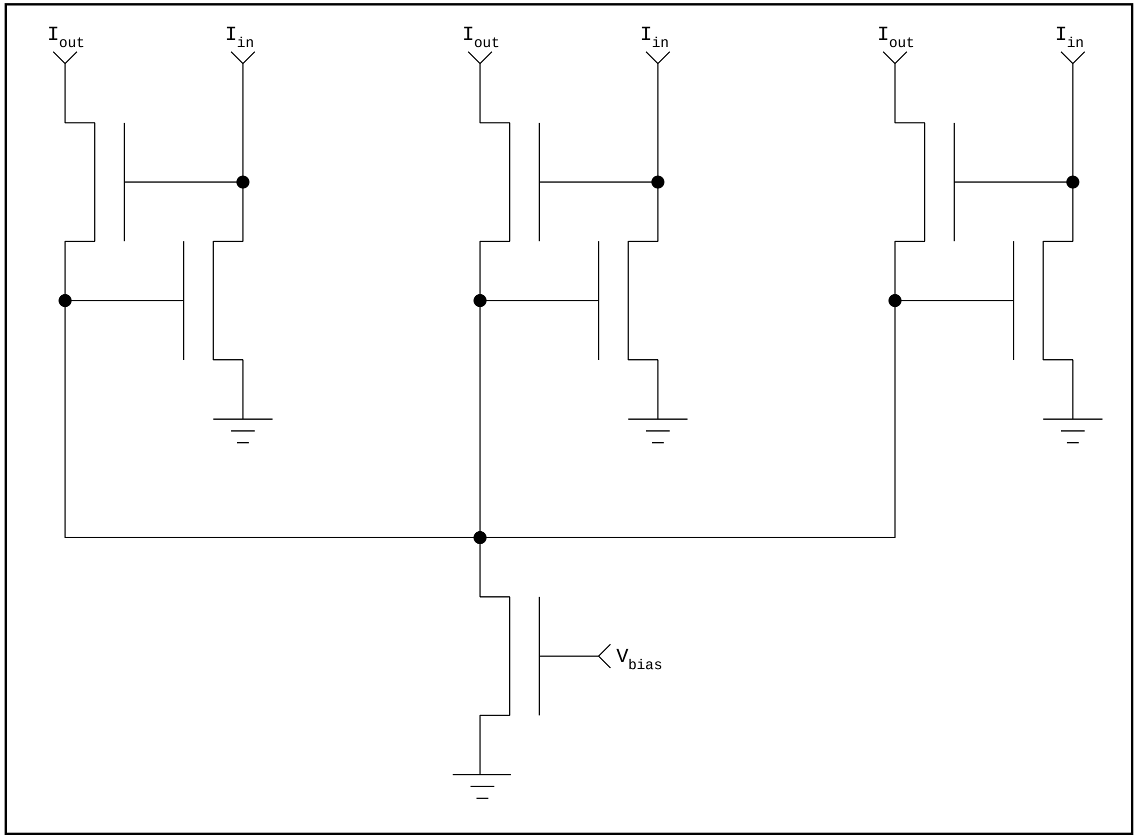
$$\frac{V^*}{R_V^*} = \frac{\delta^2}{\delta x^2 \delta y^2}\frac{V^*}{R_H^*}$$
$$V^* = -e^{\frac{-V}{U_T}}$$
$$\frac{1}{R^*} = g^* = I_S e^{\frac{V_G - V_{T0}}{nU_T}}$$

Attention: transistors must be in subthreshold for this to be applicable!

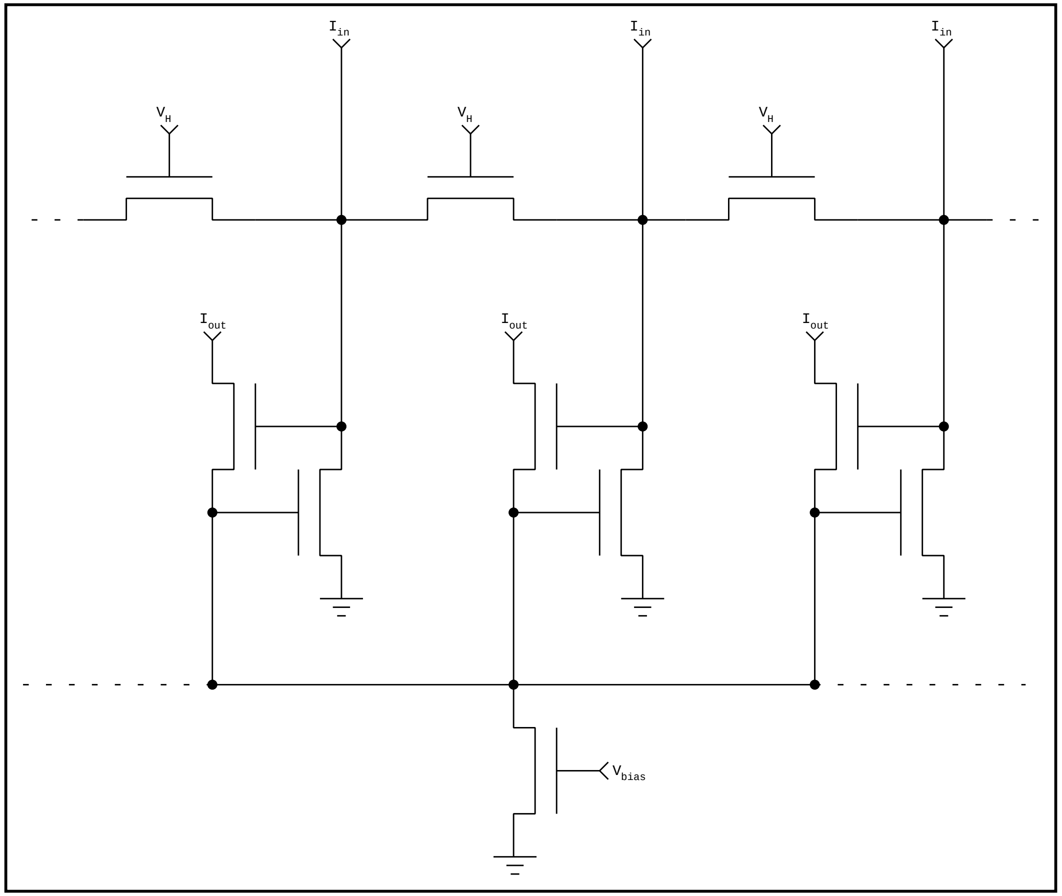
Winner Take All Principle



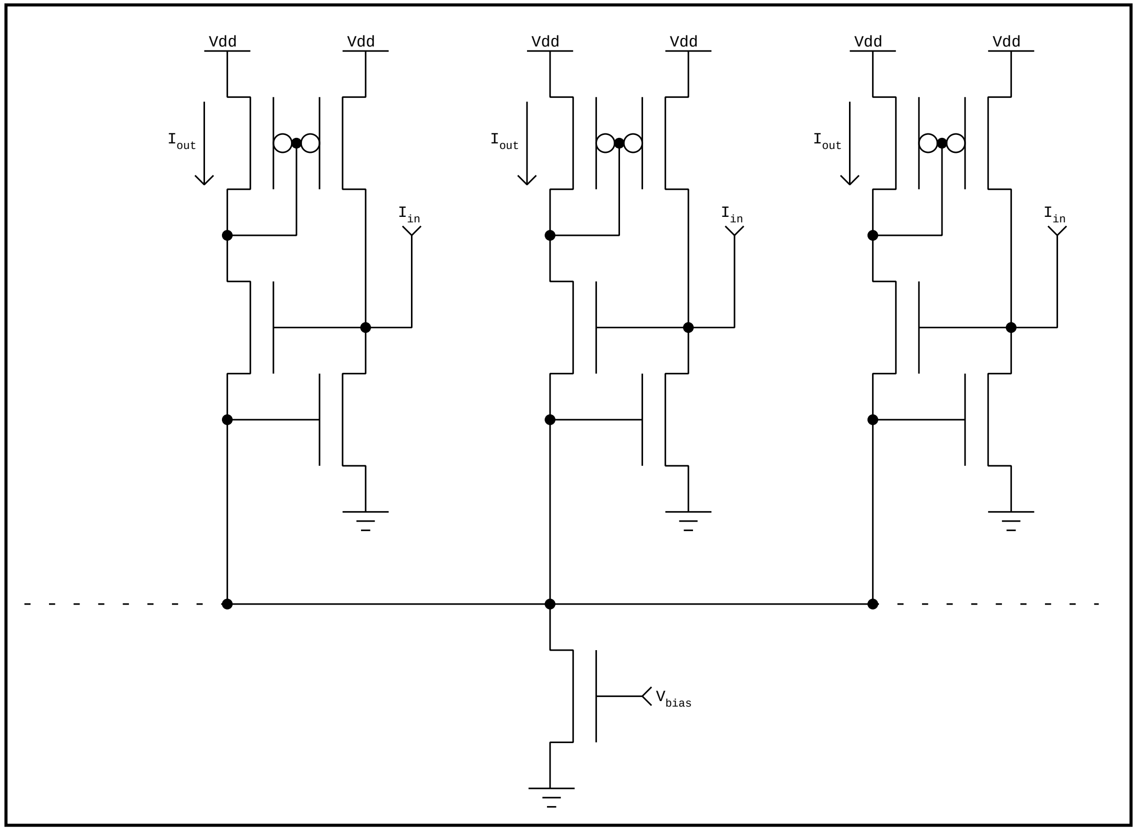
Winner Take All Basic Circuit



Smooth Cooperative Winner Take All



Hysteretic Winner Take All



Local Winner Take All Principle