ELEN 326

Current Mirrors

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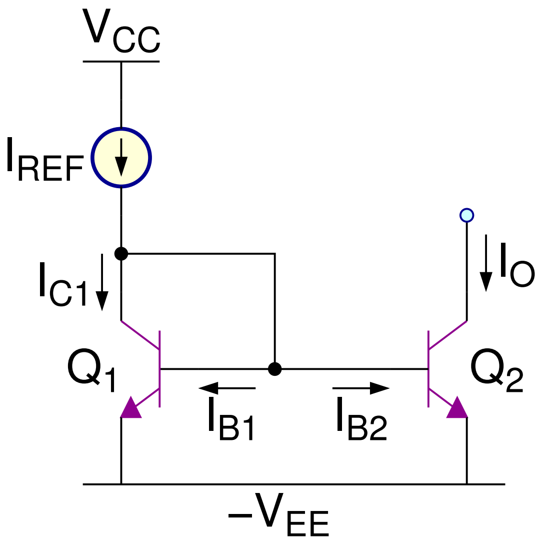
Simple Current Mirror



$$V_{BE1} = V_T \ln \frac{I_{C1}}{I_{S1}} = V_{BE2} = V_T \ln \frac{I_{C2}}{I_{S2}}$$

$$I_{S1} = I_{S2} \quad \Rightarrow \quad I_{C1} = I_{C2} = I_C$$

$$I_{B1} = I_{B2} = I_B$$

$$I_{REF} = I_C + 2I_B = I_C + \frac{2I_C}{\beta} = I_C\left(1 + \frac{2}{\beta}\right)$$

$$I_O = I_{C2} = I_C$$

$$I_O = \frac{\beta}{\beta + 2} I_{REF} = \frac{1}{1 + \frac{2}{\beta}} I_{REF}$$

$$R_o = r_{o2} = \frac{V_A}{I_{C2}}$$

$$V_{O(min)} = V_{CE2(sat)}$$

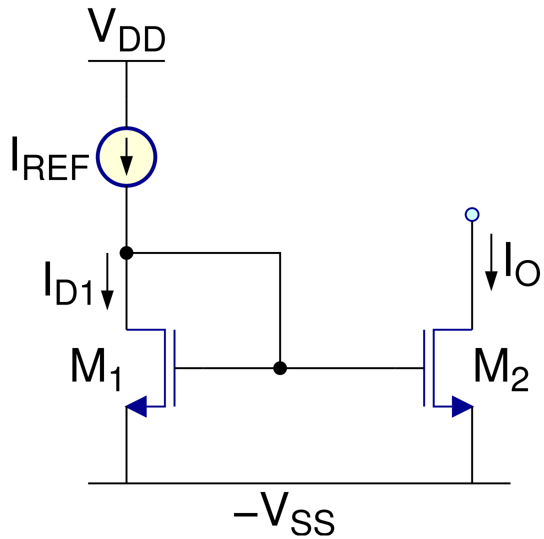
If the transistors are not identical:

$$I_O = \frac{I_{S2}}{I_{S1}} I_{REF} \frac{1}{1 + \frac{1 + (I_{S2}/I_{S1})}{\beta}}$$

Including the effect of Early voltage:

$$I_O = \frac{I_{S2}}{I_{S1}} I_{REF} \frac{1 + \frac{V_{CE2} - V_{CE1}}{V_A}}{1 + \frac{1 + (I_{S2}/I_{S1})}{\beta}}$$

Simple Current Mirror



$$V_{GS1} = V_t + \sqrt{\frac{2I_{D1}}{k'(W/L)_1}} = V_{GS2} = V_t + \sqrt{\frac{2I_{D2}}{k'(W/L)_2}}$$

$$\frac{I_{D2}}{I_{D1}} = \frac{(W/L)_2}{(W/L)_1} \quad \Rightarrow \quad \frac{I_O}{I_{REF}} = \frac{(W/L)_2}{(W/L)_1}$$

Simple Current Mirror

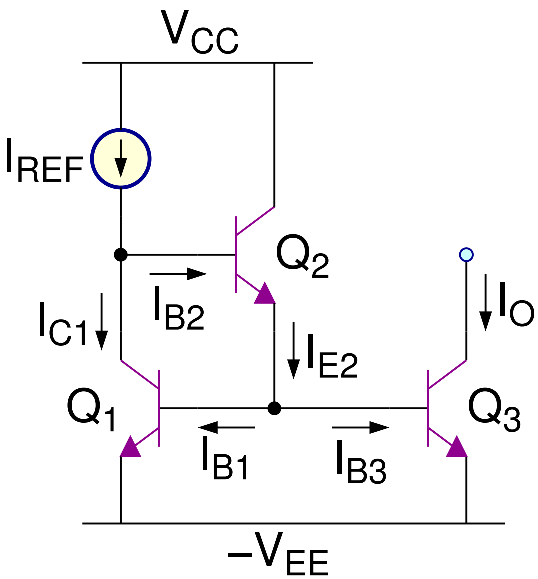
$$R_o = r_{o2} = \frac{V_A}{I_{D2}} = \frac{1}{\lambda I_{D2}}$$

$$V_{O(min)} = V_{ov} = \sqrt{\frac{2I_O}{k'(W/L)_2}}$$

Including the effect of Early voltage:

$$\frac{I_O}{I_{REF}} = \frac{(W/L)_2}{(W/L)_1}\left(1 + \frac{V_{DS2} - V_{DS1}}{V_A}\right)$$

Simple Current Mirror with Beta Helper



$$\begin{aligned} I_{REF} &= I_{C1} + I_{B2} \\ &= I_{C1} + \frac{I_{E2}}{\beta + 1} \\ &= I_{C1} + \frac{I_{B1} + I_{B3}}{\beta + 1} \end{aligned}$$

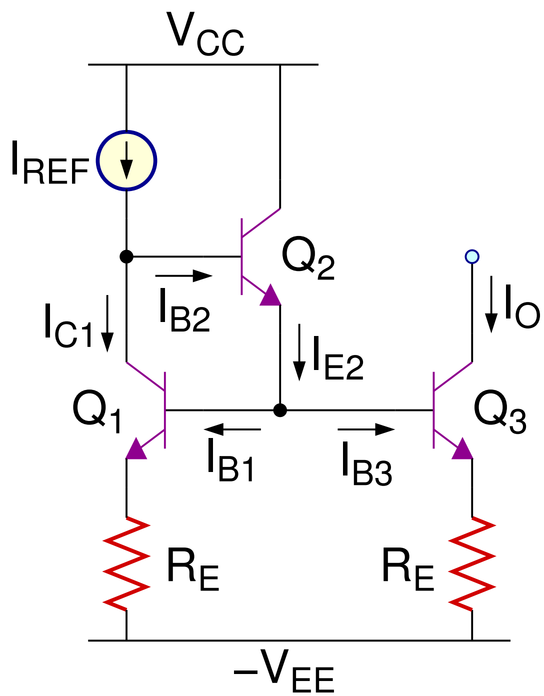
$$V_{BE1} = V_{BE3} \Rightarrow \begin{array}{l} I_{C1} = I_{C3} = I_C = I_O \\ I_{B1} = I_{B3} = I_B \end{array}$$

$$I_{REF} = I_C + \frac{2I_B}{\beta + 1} = I_C + \frac{2I_C}{\beta(\beta + 1)} = I_C\left(1 + \frac{2}{\beta(\beta + 1)}\right)$$

$$I_O = \frac{1}{1 + \frac{2}{\beta(\beta + 1)}} I_{REF} \qquad R_o = r_{o3} = \frac{V_A}{I_{C3}}$$

$$V_{O(min)} = V_{CE3(sat)}$$

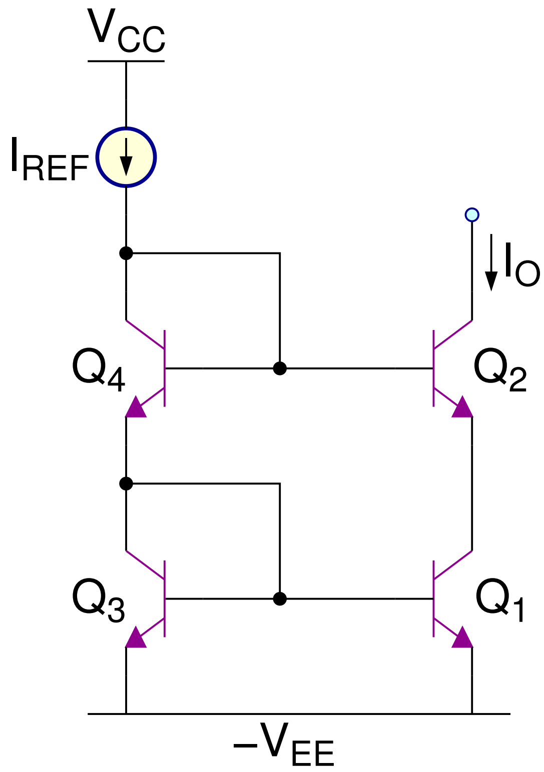
Simple Current Mirror with Degeneration



$$R_o \approx r_{o3}(1 + g_{m3}R_E) = r_{o3}\left(1 + \frac{I_{C3}}{V_T}R_E\right)$$

$$V_{O(min)} = V_{CE3(sat)} + I_{C3}R_E$$

Cascode Current Mirror

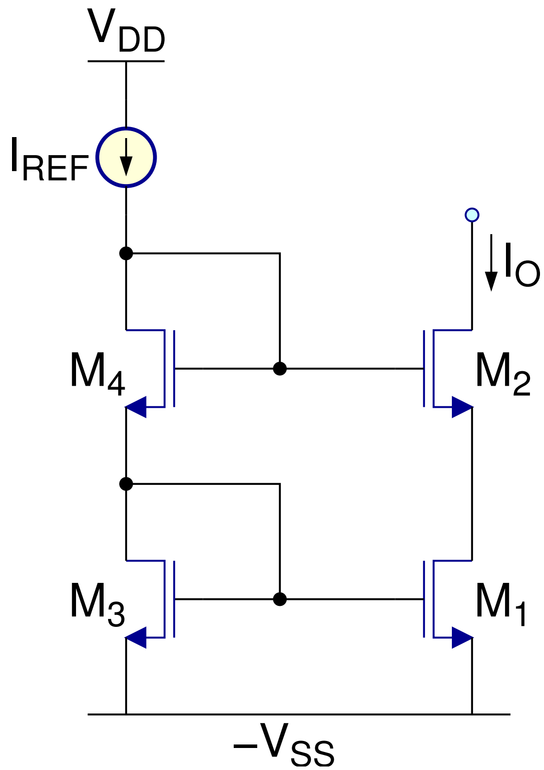


$$I_O = I_{REF}\left(1 - \frac{4\beta + 2}{\beta^2 + 4\beta + 2}\right)$$

$$R_O \approx \frac{\beta}{2} r_{o2}$$

$$V_{O(min)} \approx V_{BE(on)} + V_{CE2(sat)}$$

Cascode Current Mirror



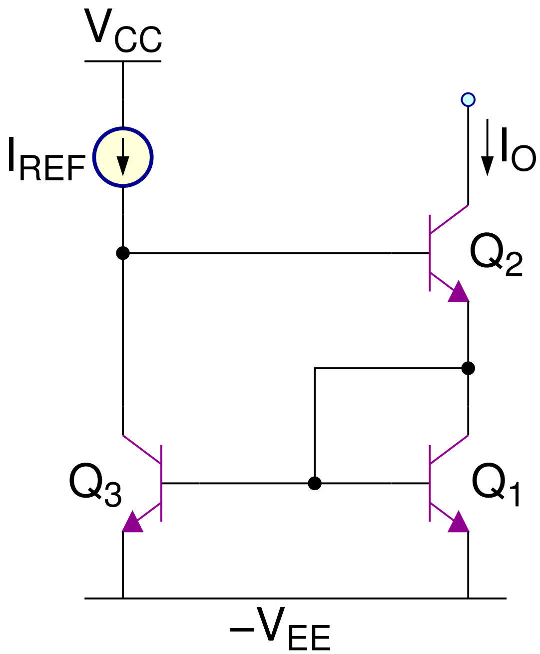
If $\mathbf{M_1}$–$\mathbf{M_4}$ are identical:

$$I_O \approx I_{REF}$$

$$R_o = r_{o1} + r_{o2} + g_{m2} r_{o1} r_{o2}$$

$$V_{O(min)} = V_t + V_{ov3} + V_{ov2}$$

Wilson Current Mirror

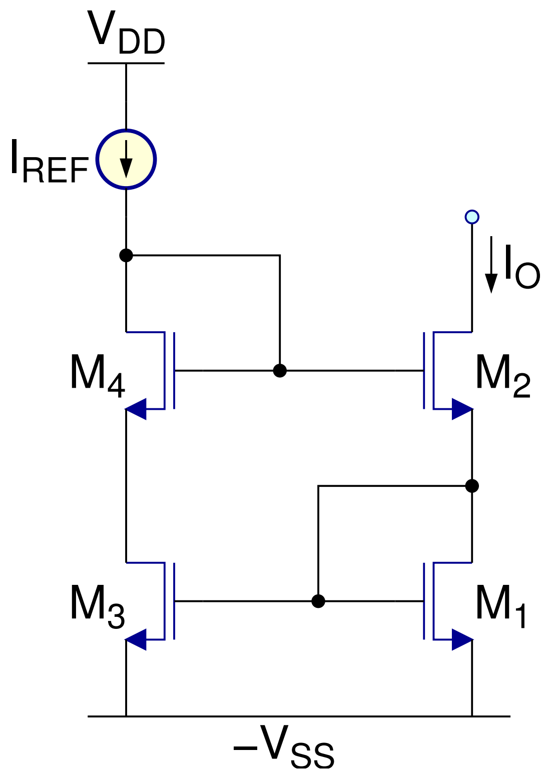


$$I_O = I_{REF}\left(1 - \frac{2}{\beta^2 + 2\beta + 2}\right)$$

$$R_o \approx \frac{\beta}{2} r_{o2}$$

$$V_{O(min)} = V_{BE(on)} + V_{CE2(sat)}$$

Wilson Current Mirror



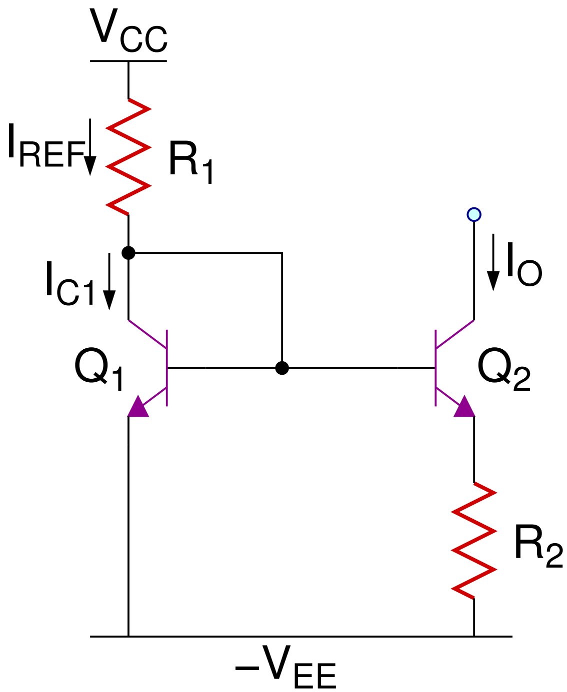
If $\mathbf{M_1}$–$\mathbf{M_4}$ are identical:

$$I_O \approx I_{REF}$$

$$R_o \approx r_{o2} + g_{m2} r_{o2} r_{o3}$$

$$V_{O(min)} = V_t + V_{ov1} + V_{ov2}$$

Widlar Current Source



$$V_{BE1} - V_{BE2} - \frac{\beta + 1}{\beta} I_O R_2 = 0$$

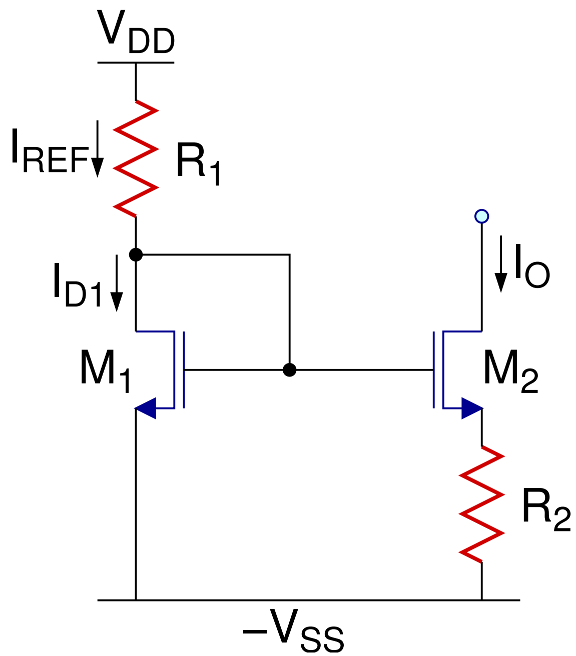
$$V_T \ln \frac{I_{REF}}{I_{S1}} - V_T \ln \frac{I_O}{I_{S1}} = \frac{\beta + 1}{\beta} I_O R_2$$

If $I_{S1} = I_{S2}$ and $\beta \rightarrow \infty$:

$$V_T \ln \frac{I_{REF}}{I_O} = I_O R_2$$

$$V_{O(min)} = V_{CE2(sat)} + I_{C2} R_2$$

Widlar Current Source



$$V_{GS1} - V_{GS2} - I_O R_2 = 0$$

$$I_O R_2 + V_{ov2} - V_{ov1} = 0$$

$$I_O = \left(\frac{-\sqrt{\dfrac{2}{k'(W/L)_2}} + \sqrt{\dfrac{2}{k'(W/L)_2} + 4R_2 V_{ov1}}}{2R_2} \right)^2$$