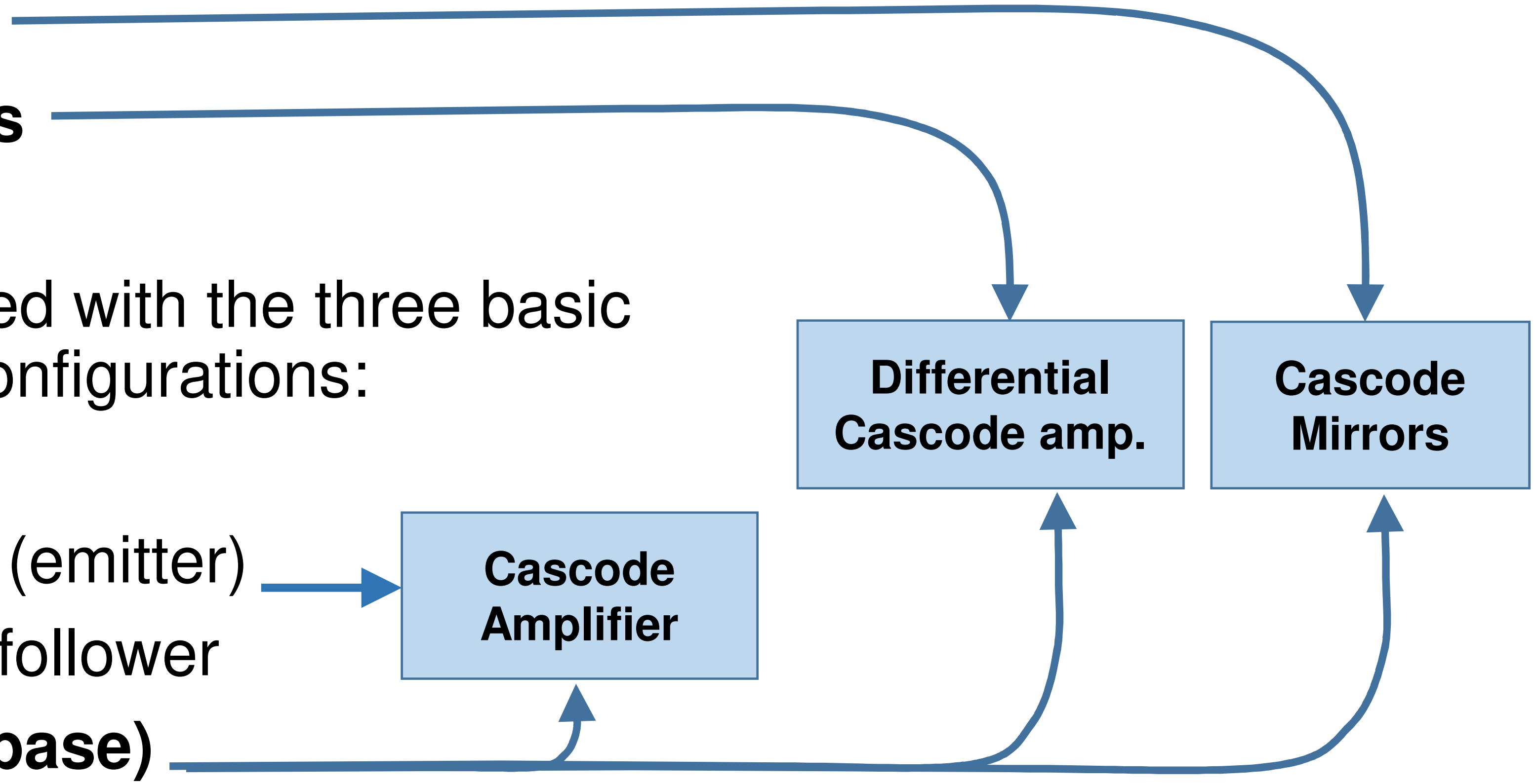
Main building blocks in analog ICs

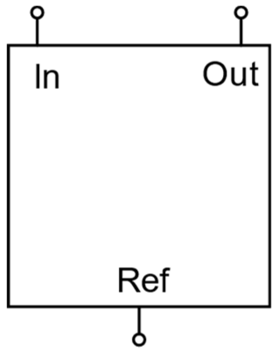
- **Current Mirrors**
- **Differential pairs**

Obviously combined with the three basic single-transistor configurations:

- Common source (emitter)
- Source (emitter) follower
- **Common gate (base)**

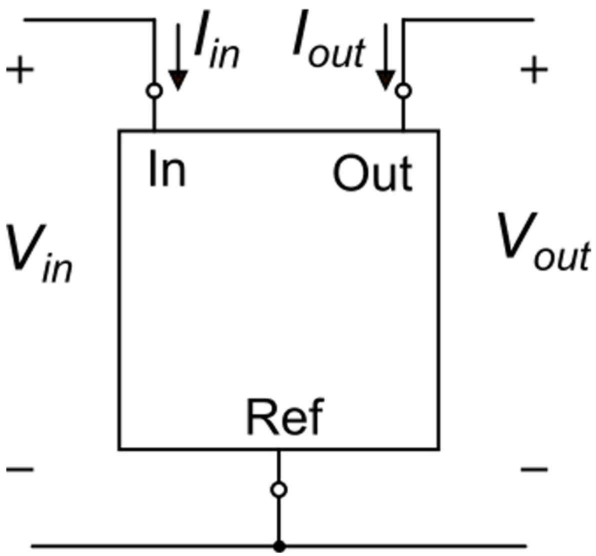


Current Mirrors: general definitions and properties



As a building block, the current mirror must have a simple topology

Voltages and currents



Ideal characteristics

$$V_{in} = 0$$

$$I_{out} = k_M I_{in}$$

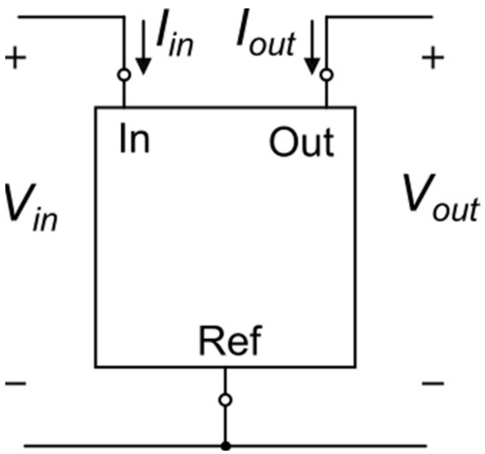
for:

$$-I_{max} < I_{in} < I_{max}$$

$$-V_{max} < V_{out} < V_{out}$$

These characteristics are generally non feasible with simple elementary circuits. They can be obtained with complex architectures (current amplifiers) that cannot be considered current mirrors anymore.

Current mirrors: n-type and p-type mirrors



$$I_{out} = k_M I_{in}$$

$$V_{out}, V_{in} > 0$$
$$I_{out}, I_{in} > 0$$

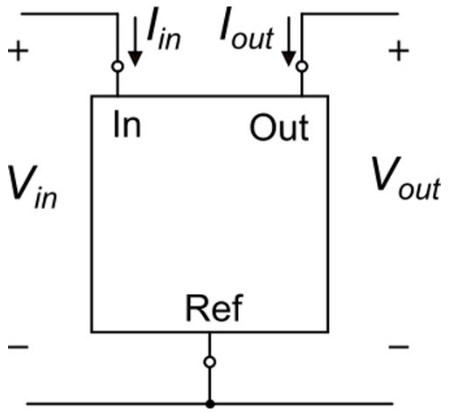
n-type:
formed mainly by n-type transistors

$$k_M > 0$$

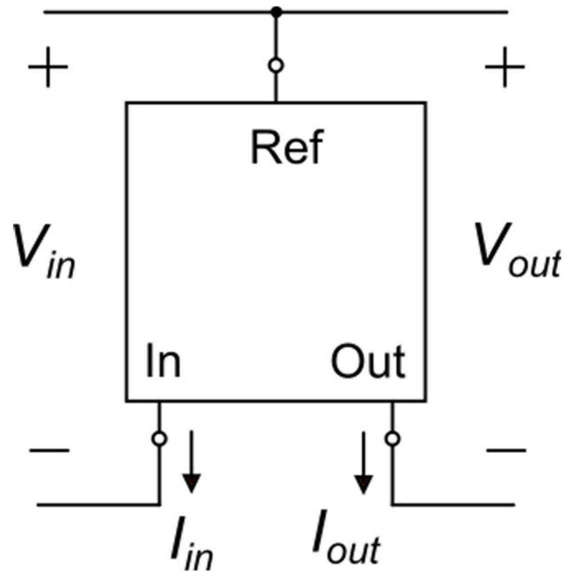
$$V_{out}, V_{in} < 0$$
$$I_{out}, I_{in} < 0$$

p-type:
formed mainly by p-type transistors

Conventions on voltage and current signs used to obtain positive values also for p-type mirrors



Convention for an n-type current mirror

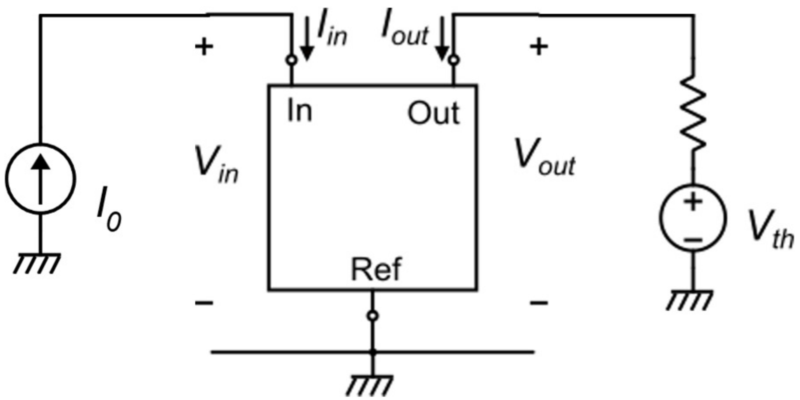


Alternative convention for a p-type current mirror

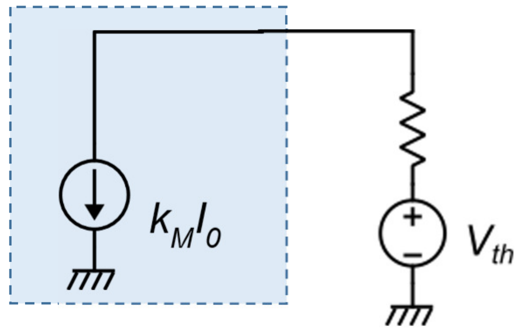
With this convention all quantities are positive also for the p-type mirror

The mirror is drawn upside-down because the voltage of the Ref terminal is greater than the voltage of In and Out ones

Current reversing function of a current mirror



Equivalent circuit seen from the mirror output terminal



This is a current **source** (the current exits from the generator)

n-type mirror is required (the input current enters the mirror)

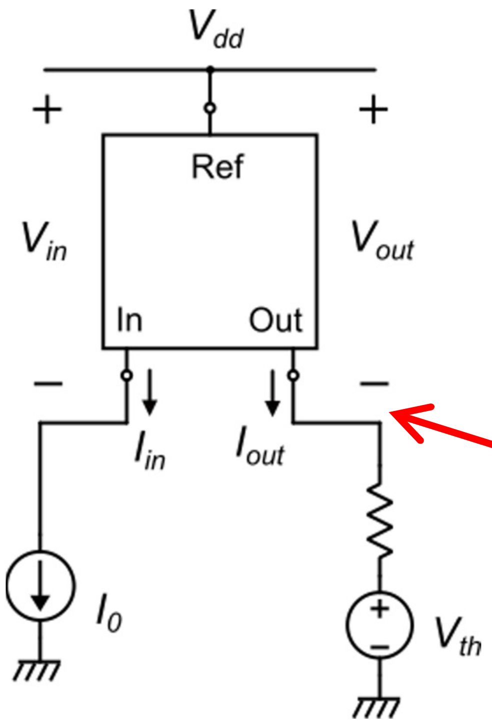
The circuit connected to the output port must be able to provide a positive V_{out}

The mirror is seen by the output circuit as a an equivalent current source. Note that now the current enters the source (**it is a sink**)

Current reversing function of a current mirror

An **n-type current mirror** transforms a current source (the current exit from the source) into a current sink (the current enter the source)

p-type

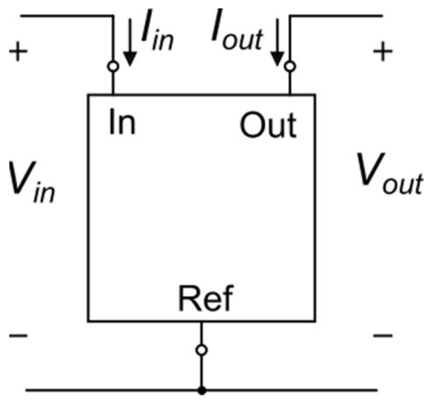


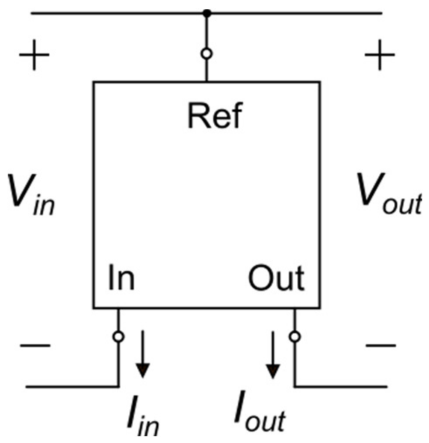
A **p-type current mirror** transforms a current sink into a current source

The generator connected to the input is "sinking" a current

The mirror is "sourcing" a current towards the output circuit

Parameters of merit for a current mirror





Ideal function: $I_{out} = k_M I_{in}$

K$_{IM}$ is a <u>nominal</u> value (gain) that should depend only on <u>simple geometrical ratios</u>.

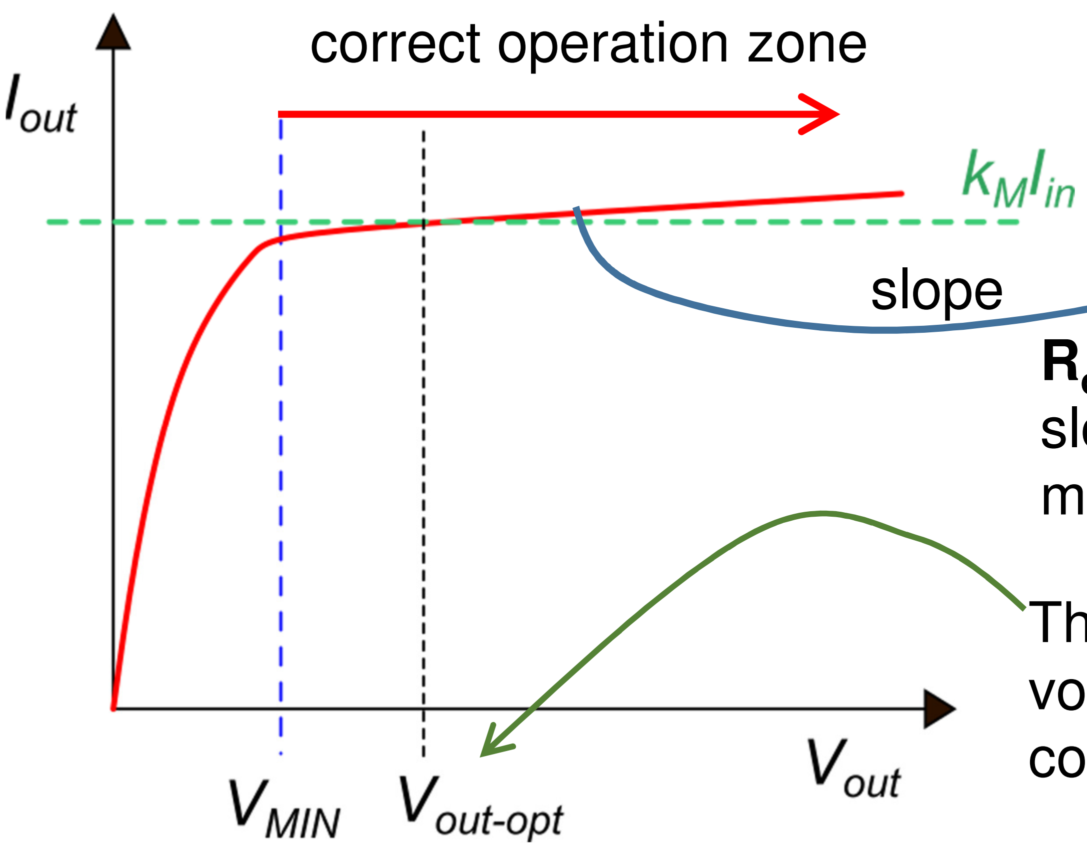
General conditions

$V_{out}, V_{in} > 0$

$I_{out}, I_{in} > 0$

1. ***V$_{in}$*** should be almost constant and be as small as possible → ***V$_{in}$***
2. The ideal function should be maintained down to very small V_{out} values. The smallest V_{out} value is indicated with ***V$_{MIN}$*** → ***V$_{MIN}$***
3. For $V_{out}>V_{MIN}$, the dependence of I_{out} on V_{out} must be the smallest as possible. → { ***R$_{out}$***, ***V$_{Th}$*** }

The typical I_{out} vs V_{out} characteristic of a current mirror

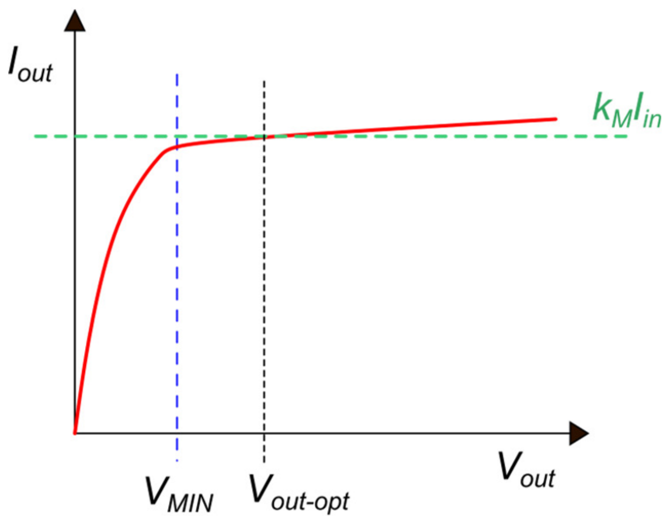


$$\frac{dI_{out}}{dV_{out}} = \frac{1}{R_{out}}$$

$\mathbf{R_{out}}$**,** which is the reciprocal of the slope in the correct operation zone, must be as large as possible

The $V_{out\text{-}opt}$ voltage is the output voltage at which the output current coincides with the ideal value $k_M I_{in}$.

The mirror "Thevenin" voltage, V_{th}



Definition: $V_{th} = I_{out} R_{out}$

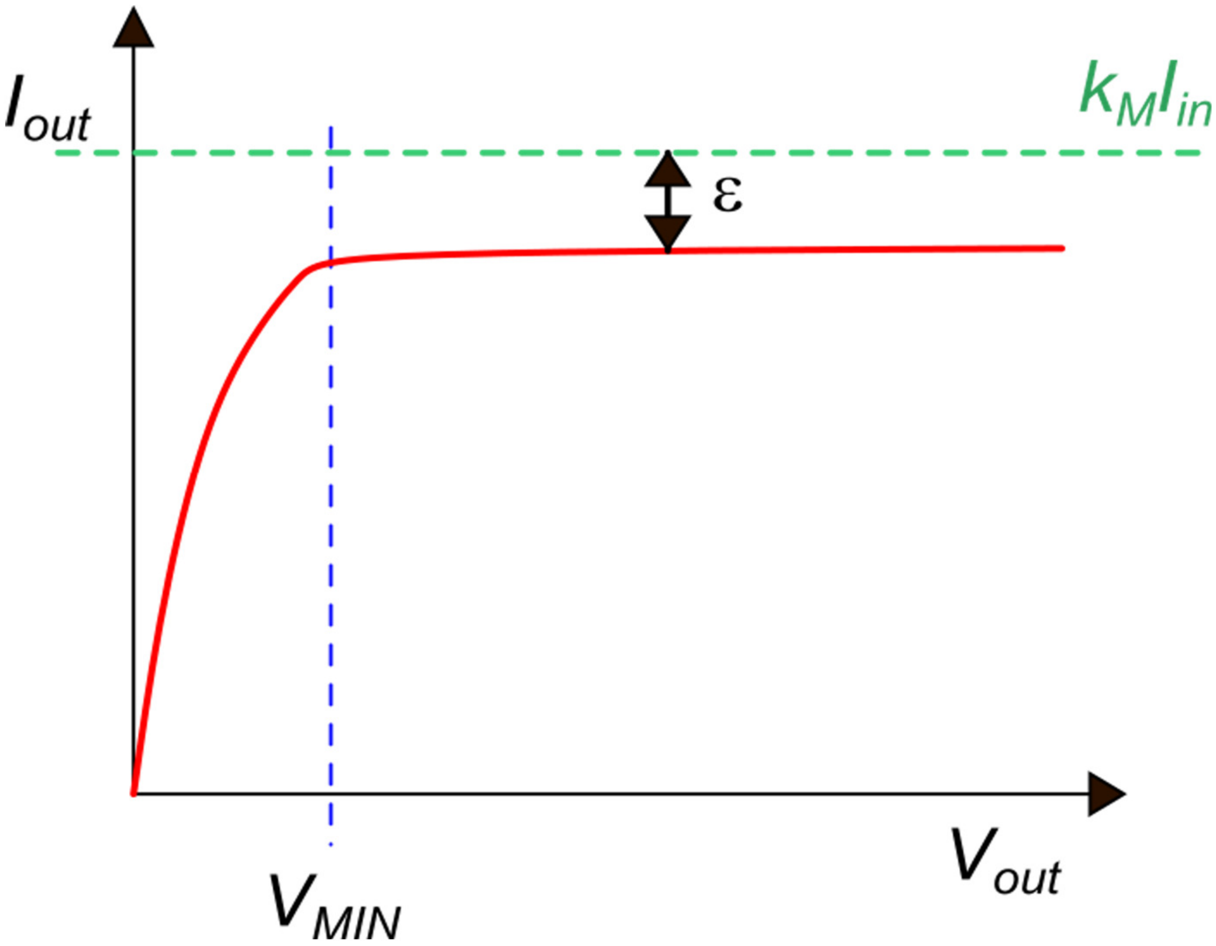
Current variation: $\Delta I_{out} = \Delta V_{out} \dfrac{1}{R_{out}}$

Relative current variation:

$$\frac{\Delta I_{out}}{I_{out}} = \Delta V_{out} \frac{1}{I_{out} R_{out}} = \frac{\Delta V_{out}}{V_{th}}$$

The Thevenin equivalent voltage allows comparing current mirrors regardless of the current magnitude they are designed for. The higher the Thevenin voltage, the more ideal the current mirror.

Presence of systematic errors



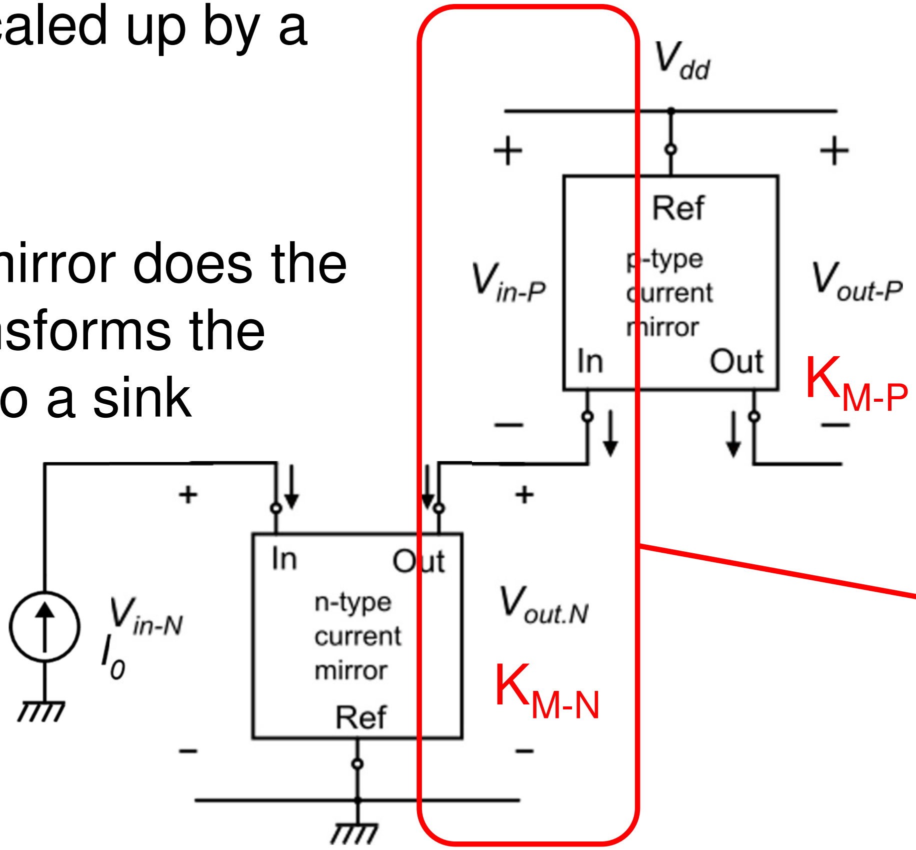
In this example, there is not an optimum voltage in the correct operating area (V_{out}>V_{MIN}) at which the output current is equal to the ideal value

Note: $\boldsymbol{k_M}$ must be a parameter that can be easily set by design. It is generally a ratio of simple device parameters:
W/L ratios in MOSFETs
area ratios in BJTs.

Role of V_{in}, V_{MIN}: an example

We need to obtain a copy of current I_0, scaled up by a factor M

A single n-mirror does the job, but transforms the a source into a sink



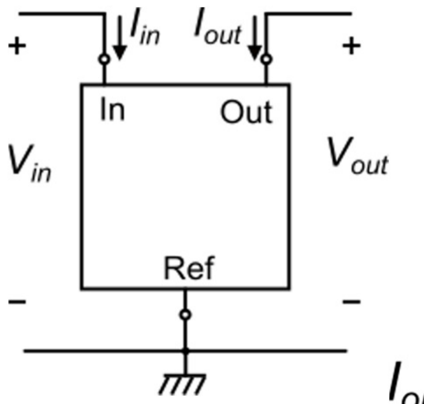
We add a p-type mirror to reverse the current source type

$$M = k_{M-N} k_{M-P}$$

$$V_{dd} = V_{out-N} + V_{in-P}$$

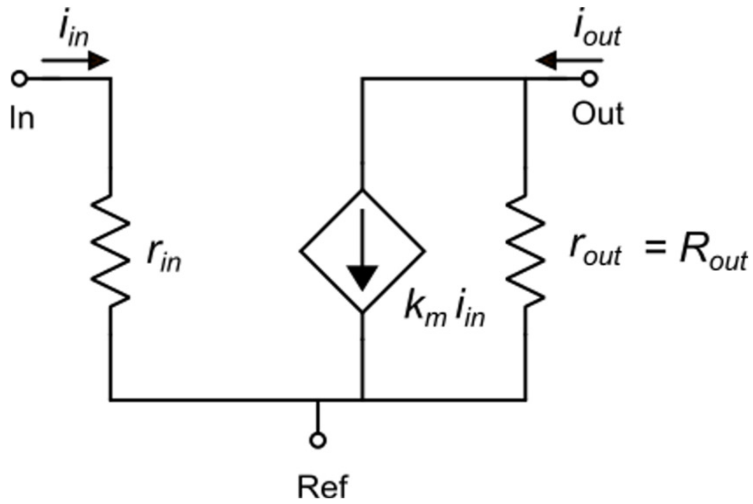
$$\min(V_{dd}) = V_{MIN-N} + V_{in-P}$$

Small signal equivalent circuit of a current mirror

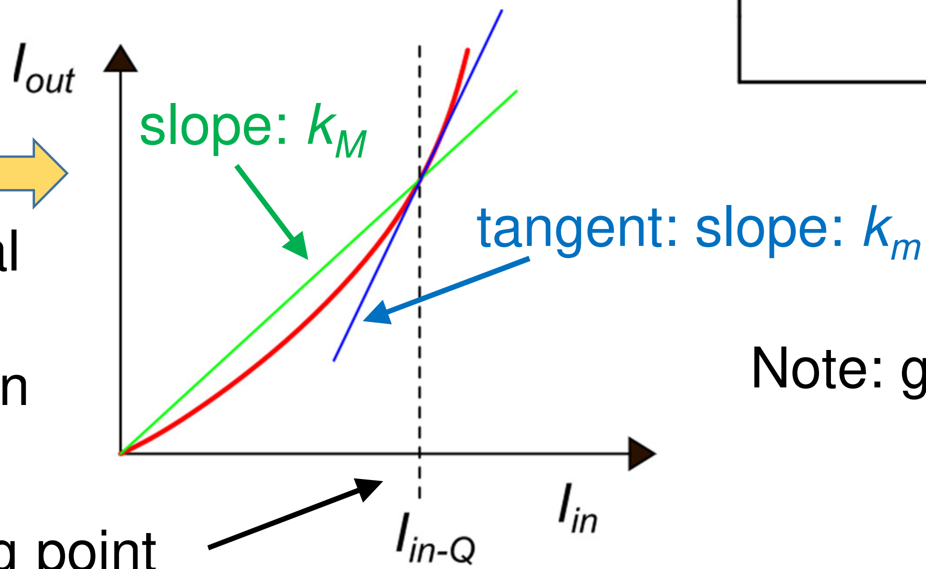


$$k_M = \frac{I_{out}}{I_{in}}$$

$$k_m = \frac{dI_{out}}{dI_{in}}$$



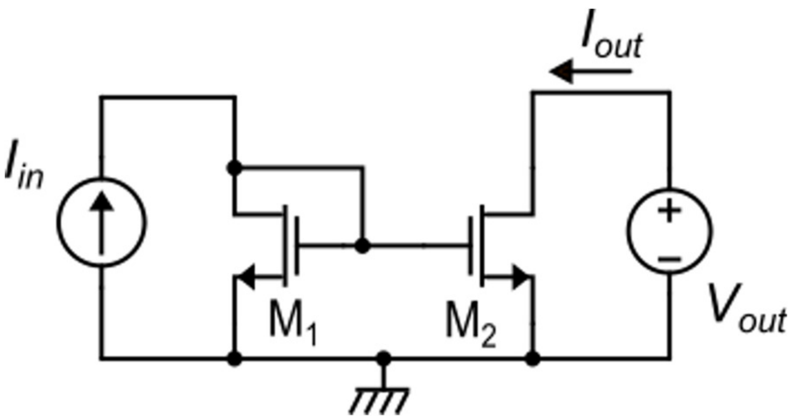
Notice: the linearity of a real current mirror is much better than in this figure



operating point

Note: generally $k_m \neq k_M$

MOSFET current mirrors: the simple mirror



strong inversion

$$I_D = \beta \frac{(V_{GS} - V_t)^2}{2}\left[1 + \lambda (V_{DS} - V_{DSAT})\right]$$

$$\beta = \mu C_{ox} \frac{W_{eff}}{L_{eff}} \cong \mu C_{ox} \frac{W}{L}$$

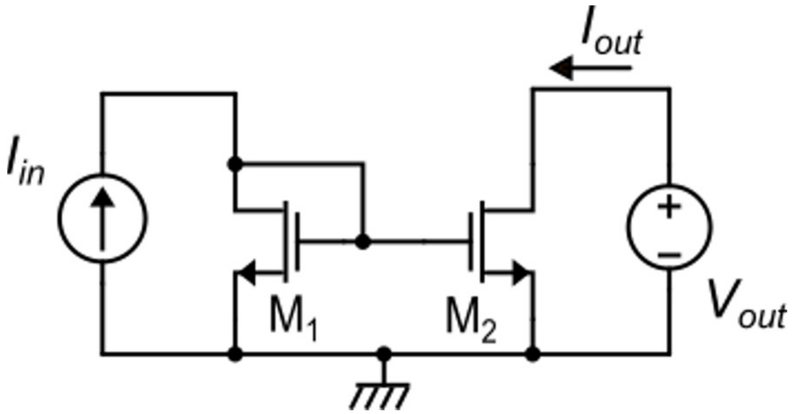
weak inversion

$$I_D = I_{SM} e^{\frac{V_{GS} - V_t}{m V_T}} \left(1 - e^{\frac{-V_{DS}}{V_T}}\right)\left[1 + \lambda (V_{DS} - V_{DSAT})\right]$$

$$I_{SM} = \mu_n C_{ox} (m-1) V_T^2 \frac{W_{eff}}{L_{eff}} = \beta (m-1) V_T^2$$

$$I_D = \beta f (V_{GS} - V_t, V_{DS})$$

Simple MOSFET current mirror



$$I_D = \beta f\left(V_{GS} - V_t, V_{DS}\right)$$

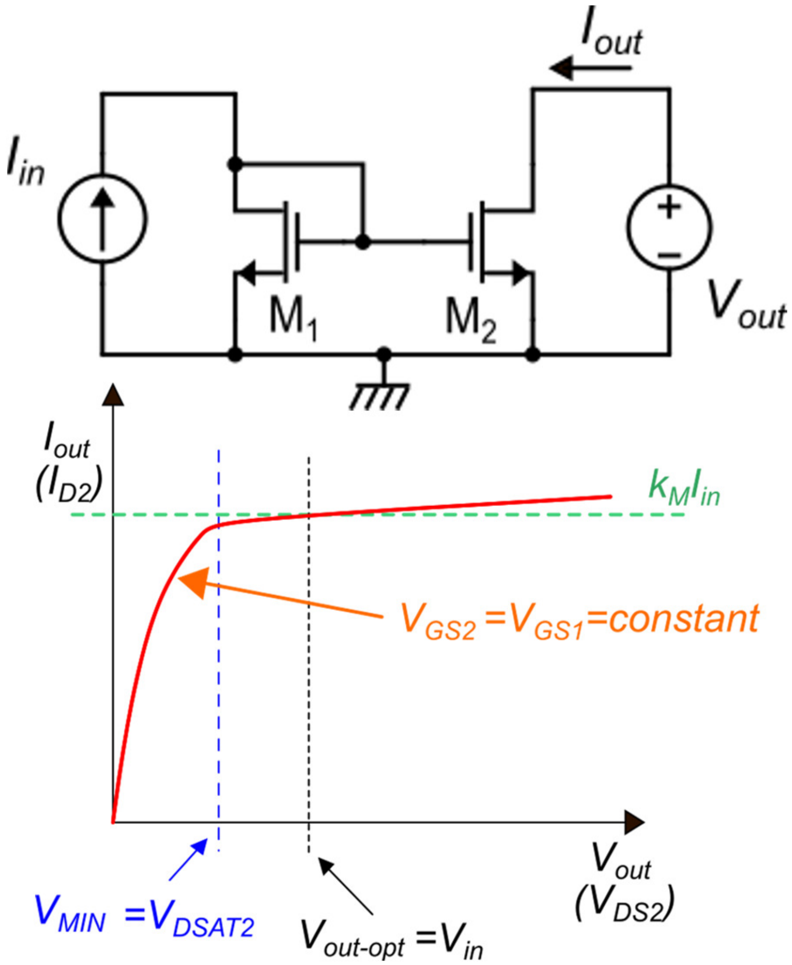
$$I_{out} = \beta_2 f\left(V_{GS} - V_t, V_{DS2}\right) = \beta_2 f\left(V_{GS} - V_t, V_{out}\right)$$

$$I_{in} = \beta_1 f\left(V_{GS} - V_t, V_{DS1}\right) = \beta_1 f\left(V_{GS} - V_t, V_{in}\right)$$

For V_{out}=V_{in} $\quad \dfrac{I_{out}}{I_{in}} = \dfrac{\beta_2}{\beta_1} = \dfrac{W_2 / L_2}{W_1 / L_1} = k_M$

$$V_{out-opt} = V_{in}$$

Parameters of the simple MOSFET current mirror



$$V_{in} = V_{GS1} = V_t + (V_{GS} - V_t)$$

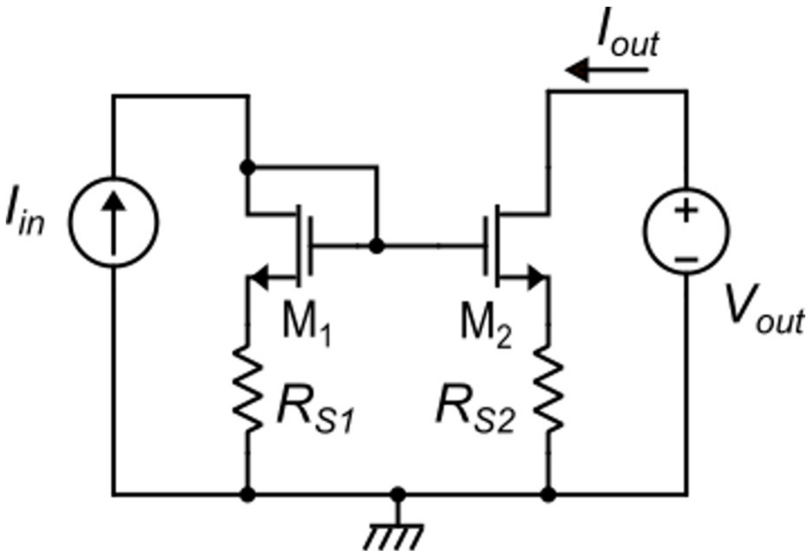
$$V_{MIN} = V_{DSAT2}$$

In strong inversion

$$V_{GS} - V_t = \sqrt{\frac{2I_{in}}{\beta_1}}$$

$$\begin{cases} R_{out} = r_{d2} = \dfrac{1}{\lambda_2 I_{out}} \\ V_{th} = I_{out} R_{out} = \dfrac{1}{\lambda_2} \end{cases}$$

Increasing R_{out}: source degeneration



$$R_{out} = R_{S2} + r_{d2}\left(1 + g_{m2}R_{S2}\right)$$

$$R_{out} \cong r_{d2}\left(1 + g_{m2}R_{S2}\right)$$

The output resistance is increased by a factor $(1+g_{m2}R_{S2})$ with respect to the simple current mirror

In order to have a linear behavior, so that $I_{out}=k_M I_{in}$, we need that:

$$V_{GS1} = V_{GS2} \Rightarrow V_{S2} = V_{S1}$$

In this way, we can apply the same formulas of the simple mirror for I_{D1} and I_{D2} that give:

$$k_M = \frac{\beta_2}{\beta_1}$$

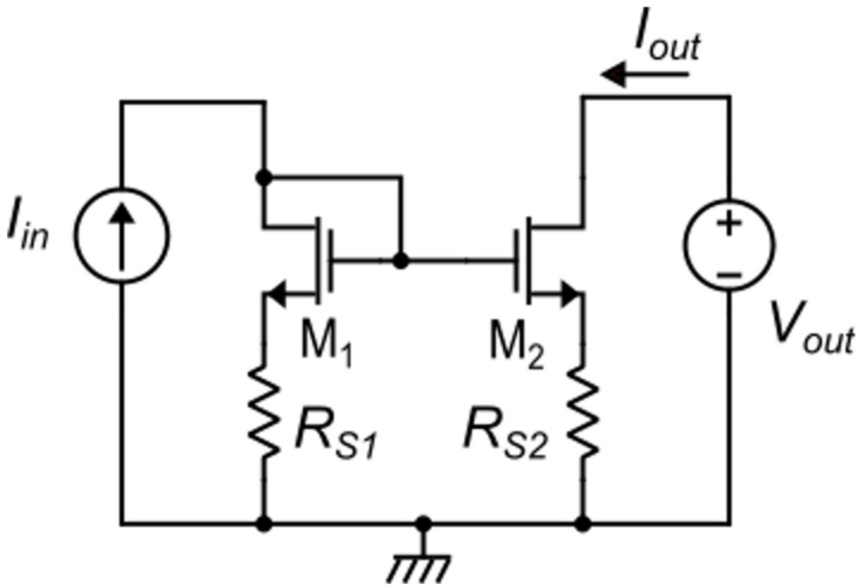
Notice:

$$V_{S2} = V_{S1} \Rightarrow R_{S1}I_{in} = R_{S2}I_{out}$$

design rule

$$\frac{R_{S1}}{R_{S2}} = \frac{I_{out}}{I_{in}} = k_M$$

Increasing R_{out}: source degeneration



$$V_{in} = V_{GS1} + R_1 I_{in}$$

Notice: $R_{out} \cong r_{d2}\left(1 + g_{m2} R_{S2}\right)$

But: $g_{m2} R_{S2} = \dfrac{I_{D2} R_{S2}}{V_{TE2}}$

Unfortunately, V_{MIN} and V_{in} are larger in this mirror:

$$V_{out} = V_{DS2} + R_2 I_{out}$$

when V_{out} reduces, Iout is nearly constant, then this term is almost constant and it is V_{DS2} to dimmish.

The mirror starts to fail at a V_{out} value that make M_2 enter triode region

$$V_{MIN} = V_{DSAT2} + R_2 I_{out}$$

To get a large output resistance boosting factor ($1+g_{m2}R_{D2}$, it is necessary to make $R_{D2}I_{out} >> V_{TE}$

In practice, $R_{D2}I_{out}$ ($=R_{D1}I_{in}$) cannot be too large to avoid increasing V_{in} and V_{MIN} too much