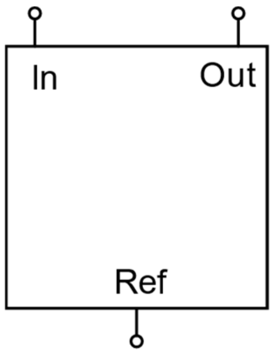
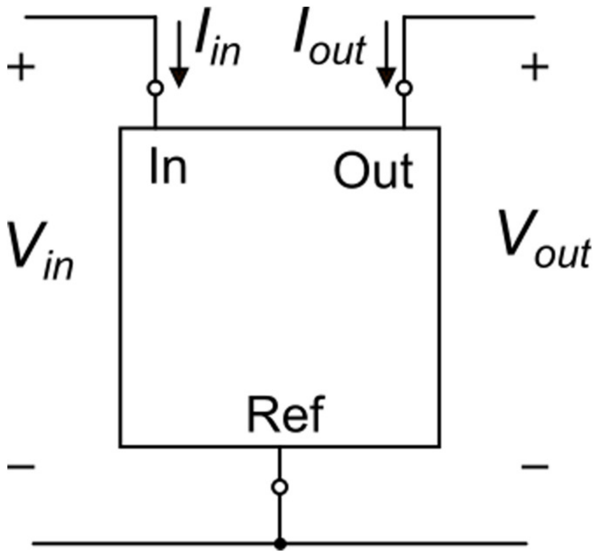
# Current Mirrors: general definitions and properties




Desired characteristics

$$V_{in} = 0$$

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

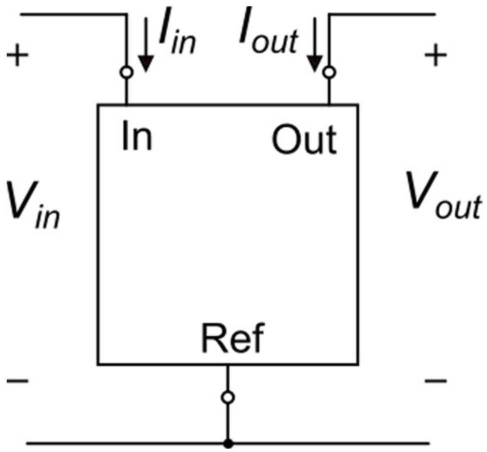
for:

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

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

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

# 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

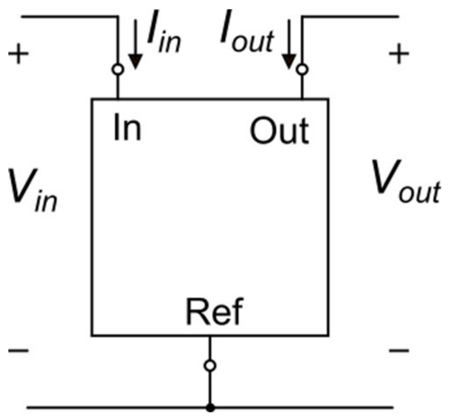
$$k_M > 0$$

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

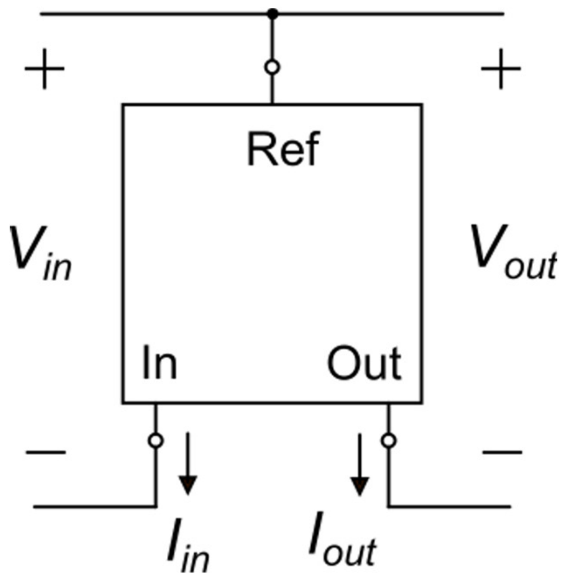
$I_{out}, I_{in} < 0$

**p-type**:
formed mainly by p-type transistors

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



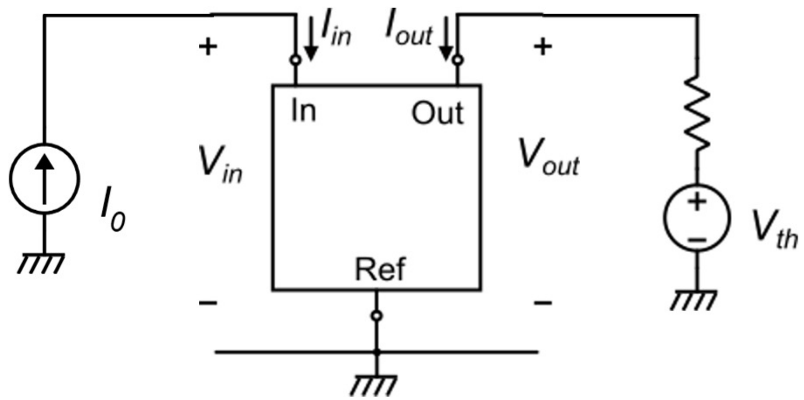

Convention for an n-type current mirror



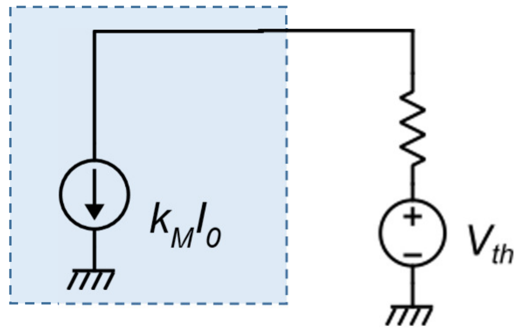

Convention for a p-type current mirror

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

# 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)

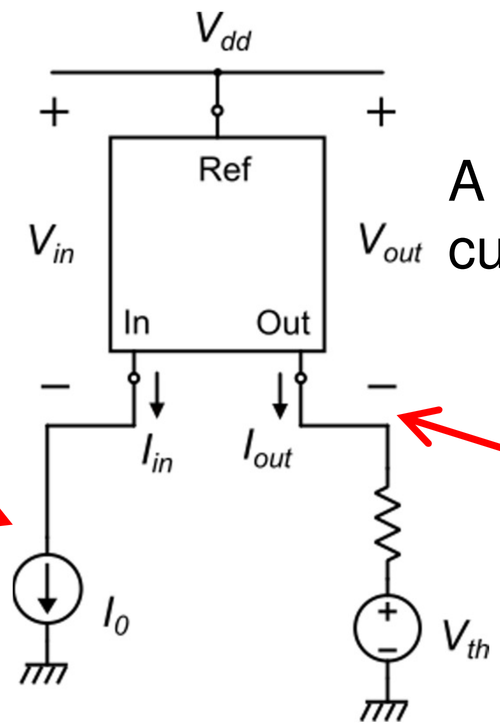
n-type mirror is required (the input current enters the mirror)

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 (**=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)

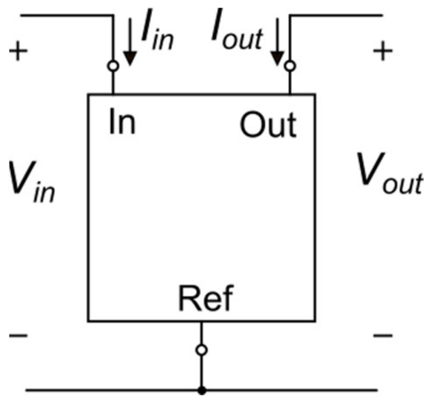


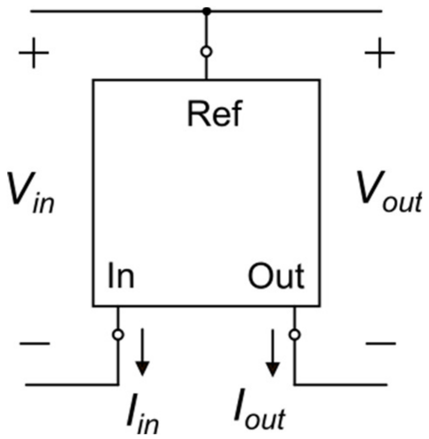

A p-type current mirror tranforms a current sink into a current source

This generator is "sinking" a current

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

# Parameters of merit for a current mirror



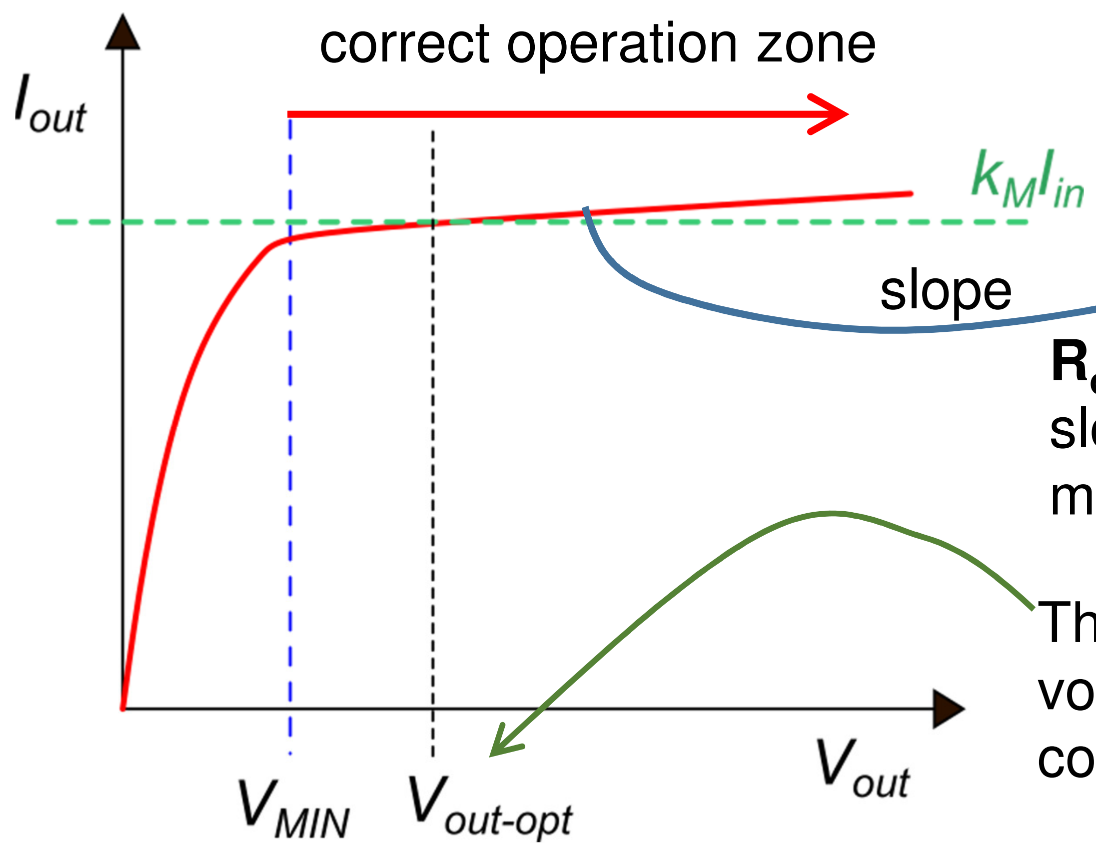

Ideal function: $I_{out} = k_M I_{in}$

General conditions

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

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

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

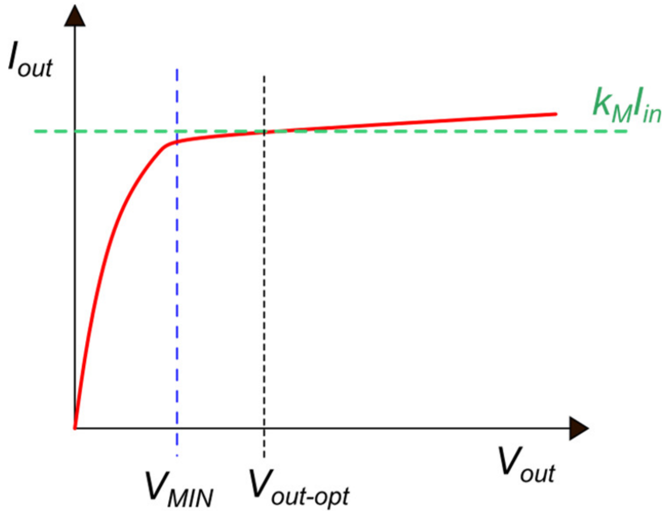



$$\frac{dI_{out}}{dV_{out}} = \frac{1}{R_{out}}$$

$\mathbf{R_{out}}$, 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: $V_{th} = I_{out} R_{out}$

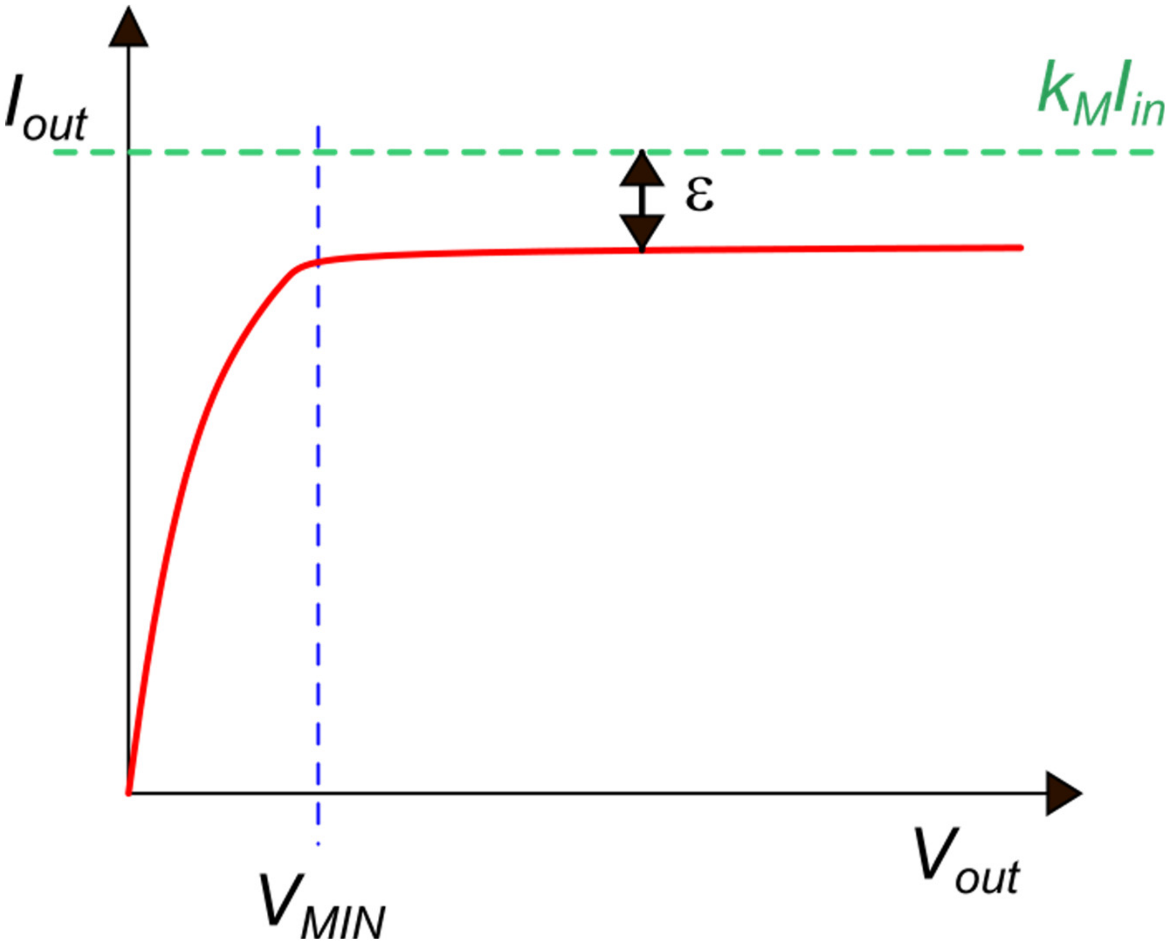
current variation: $\Delta I_{out} = \Delta V_{out} \dfrac{1}{R_{out}}$

**<u>relative</u>** 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 to compare 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

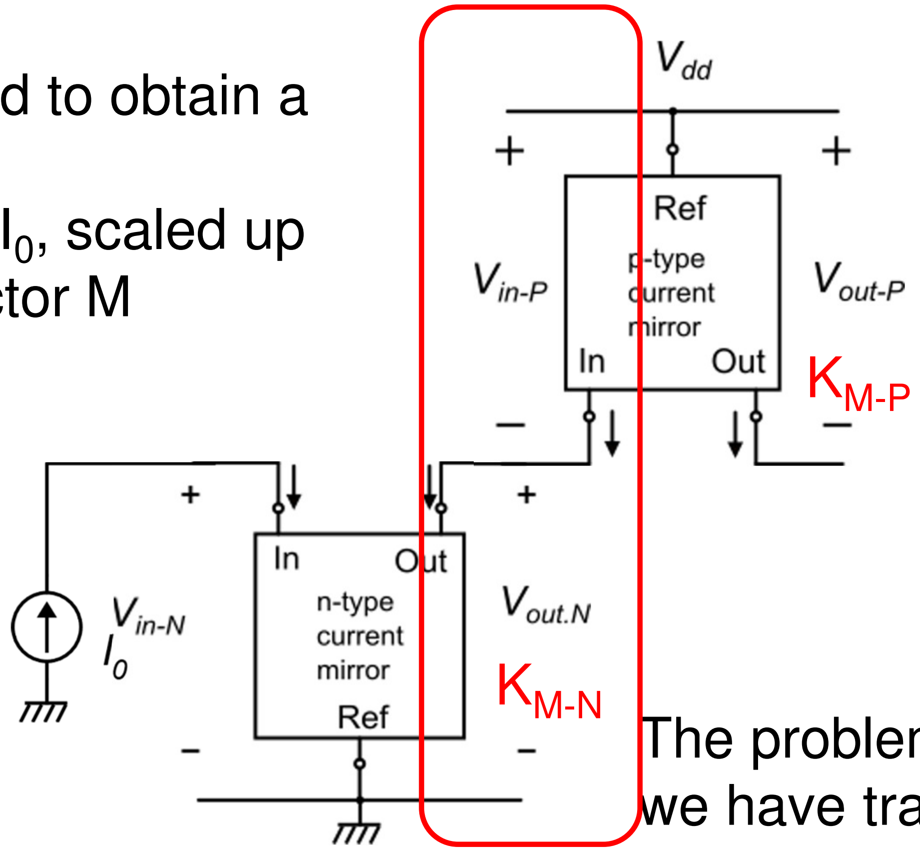



There is not an optimum voltage in the correct operating area ($V_{out}$>$V_{MIN}$) at which the output currebt is equal to the ideal value

**$k_M$** must be a parameter that can be easily set by design. It is generally a ratio of simple device parameters (b in MOSFETs, area 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




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

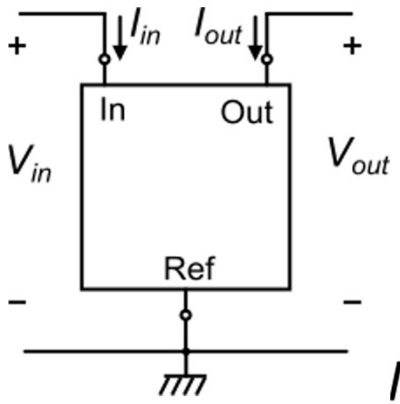
$$M = k_{M-N} k_{M-P}$$

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

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

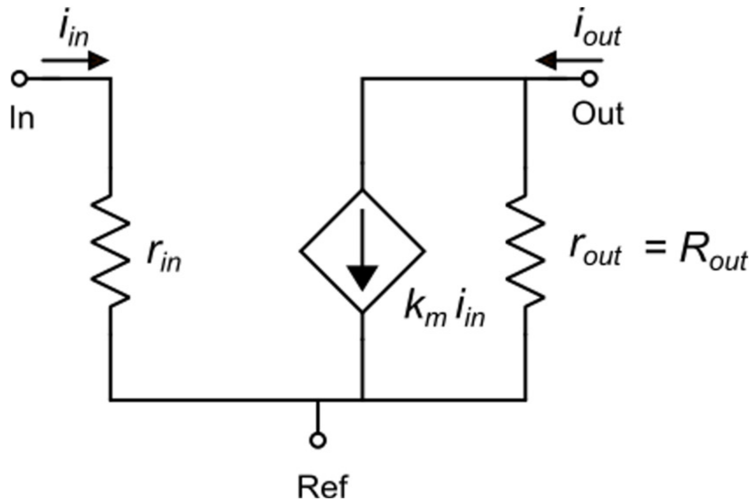
The problem is that we have transformed a source into a sink

# Small signal equivalent circuit of a current mirror

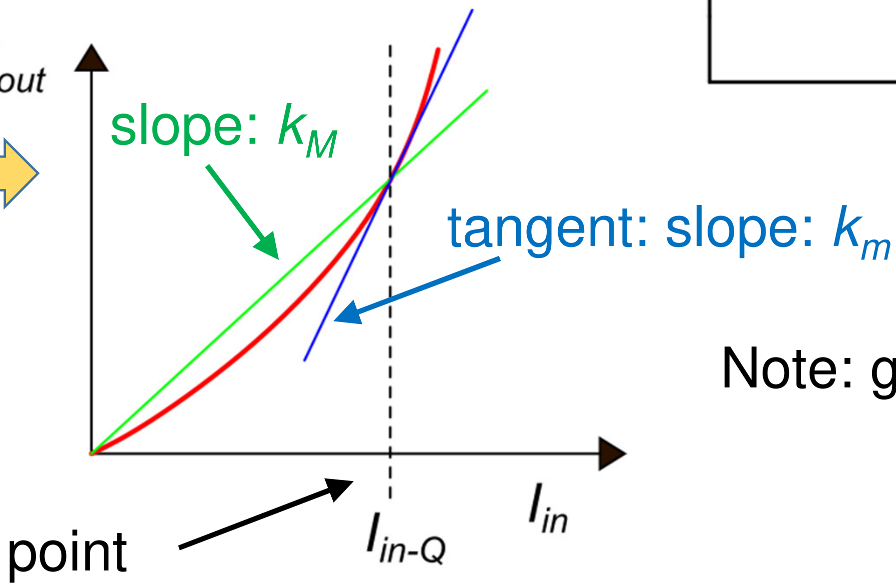



$$k_M = \frac{I_{out}}{I_{in}}$$

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

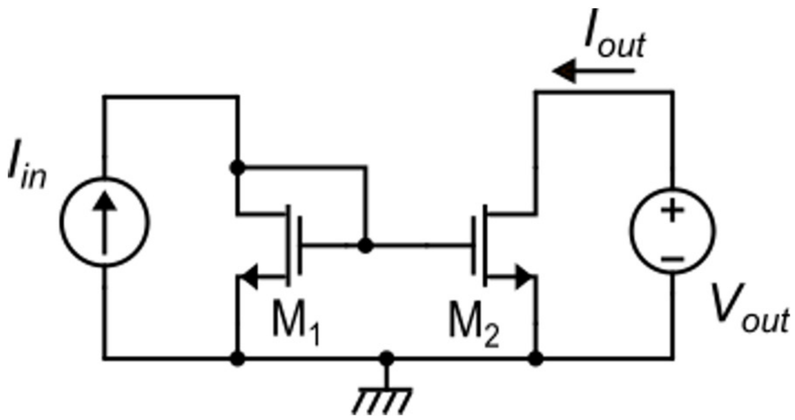



Notice: the linearity of a real current mirror is much better than in this figure




Note: generally $k_m \neq k_M$

# MOSFET current mirrors: the simple mirror




strong inversion

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

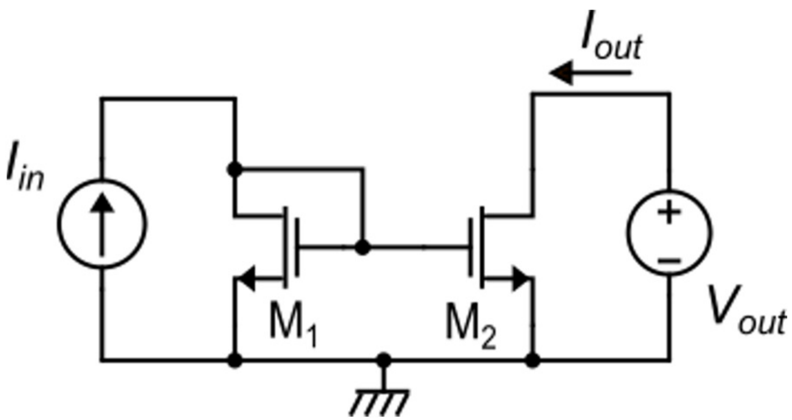
weak inversion

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

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

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

# Simple MOSFET current mirror




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

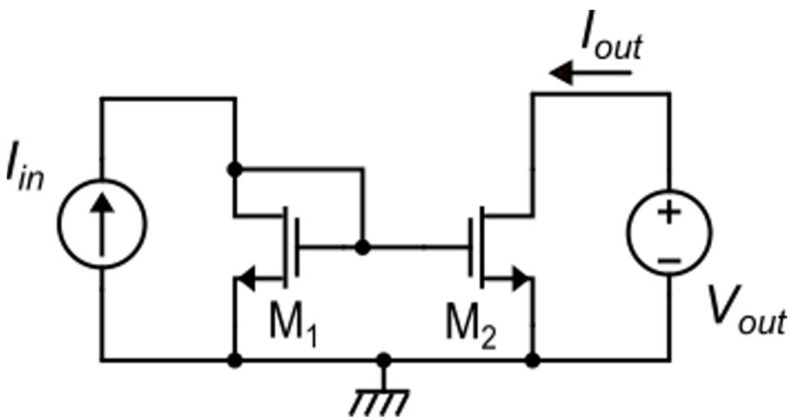
$$I_{out} = \beta_2 f\left(V_{GS} - V_t, V_{DS2}\right) = \beta_2 f\left(V_{GS} - V_t, V_{out}\right)$$

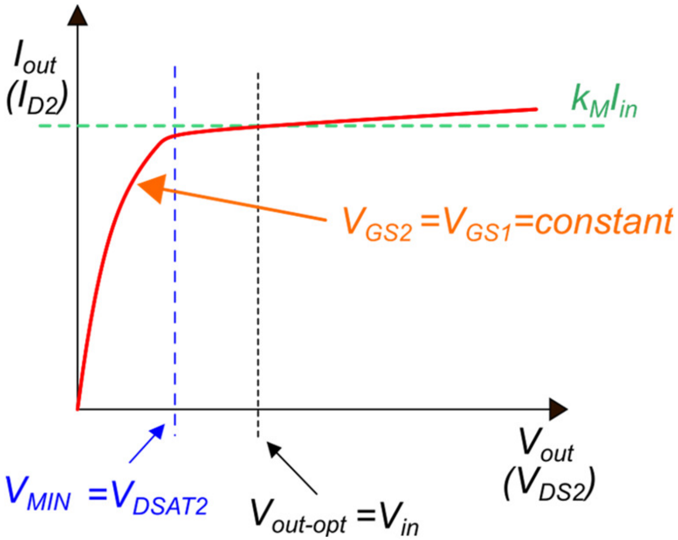
$$I_{in} = \beta_1 f\left(V_{GS} - V_t, V_{DS1}\right) = \beta_1 f\left(V_{GS} - V_t, V_{in}\right)$$

For $V_{out}=V_{in}$ $\quad \dfrac{I_{out}}{I_{in}} = \dfrac{\beta_2}{\beta_1} = k_M$

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

# Parameters of the simple MOSFET current mirror



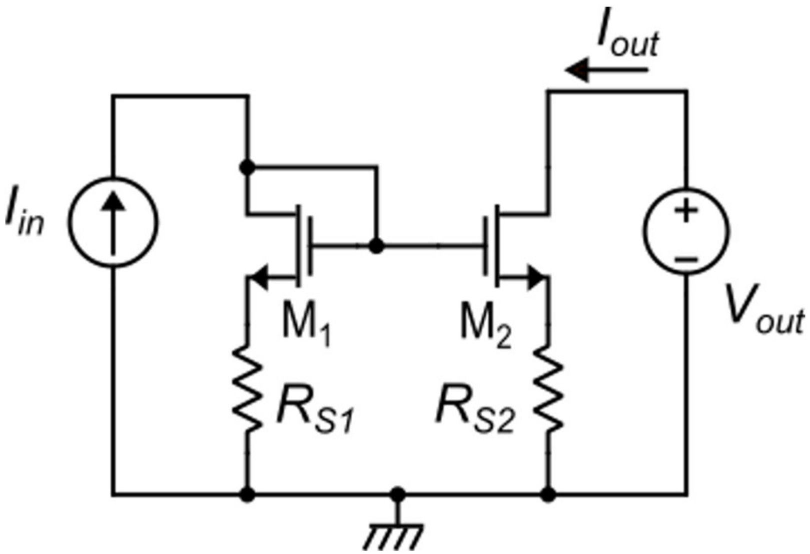

$$V_{in} = V_{GS1} = V_t + \left(V_{GS} - V_t\right)$$

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

$$R_{out} = r_{d2} = \frac{1}{\lambda_2 I_{out}}$$

$$V_{th} = I_{out} R_{out} = \frac{1}{\lambda_2}$$

# 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:

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

Notice:

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

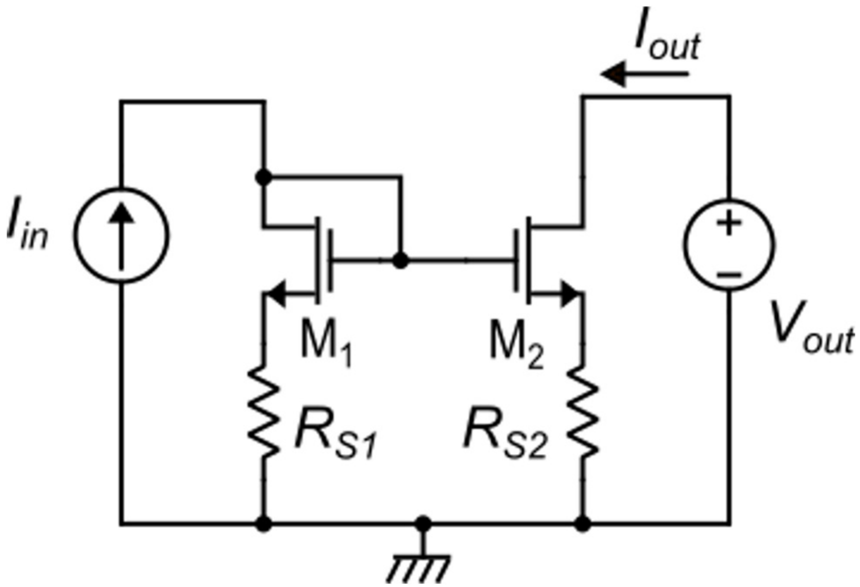
design rule

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

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

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

# 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:

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

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

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

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

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