Let's start with a current source (I-source). We frequently assume an ideal source (or sink).

- A real source has:
  \[ (V_0)_{\text{min}} = \min \text{ output voltage for } I_6 \text{ with given } R_{\text{out}} \]
  \[ (V_0)_{\text{max}} = \max \text{ output voltage} \ldots \]

  \[ R_{\text{out}} = \text{small-signal impedance looking into } V_0 \text{ terminal.} \]

  Ideally: \( (V_0)_{\text{min}} \to -\infty \); \( (V_0)_{\text{max}} \to \infty \); \( R_{\text{out}} \to \infty \).

For the nmos source (I use the term source for both "sources" and "sinks"):

\[ SSM \]

\[ V_0 \quad \text{since } V_6 = DC \]

\[ R_{\text{out}} = \frac{1}{2I_0} \]

\[ V_0 \quad \Rightarrow \text{small-signal} \]

\[ V_{\text{gs}} \to 0 \]

- \( (V_0)_{\text{min}} \) at triode boundary: \( V_{\text{gs}} = (V_0)_{\text{min}} = V_6 - V_t \)

- Recall: \( V_{\text{gs}} = V_t + \sqrt{\frac{I_0}{\kappa}} = V_t + V_0 \) \( \in \) "overdrive".

\[ \Rightarrow (V_0)_{\text{min}} = V_0 \]
• \((V_0)_{\text{max}}\): depends on the process. Generally, when operating with rated power supplies for the process, \((V_0)_{\text{max}}\) can be ignored. Generally limited by other circuitry.

• Need to generate \(V_0\): DC gate voltage; use i-mirror to allow a single accurate source to bias multiple circuits.

- From "op-mode review":
  \[
  i_0 = \frac{K_2}{K_1} I_b = \frac{(w/L)_2}{(w/L)_1} I_b \Rightarrow \text{if both active neglecting 2.}
  \]

- SSM:

- \(g_m, V_b\) term can be drawn as resistor \(\frac{1}{g_m}\).

\[
\begin{align*}
  1 & \quad 1 \\
  g_m V_b & \quad R_{ds_1} \\
  \frac{1}{g_m} & \quad R_{ds_1}
\end{align*}
\]

\[
\begin{align*}
  V_b & = 0 \\
  R_0 & = R_{ds_2}
\end{align*}
\]

\[
\begin{align*}
  V_b & = 0 \quad \Rightarrow \frac{1}{g_m} \left( R_{ds_1} + \frac{1}{g_m} \right) \quad \text{zero current} \\
  V_b & = 0 \quad \text{(as expected, with } V_b = \text{DC.)}
\end{align*}
\]

\[
(V_0)_{\text{min}} = V_{ou2} = \sqrt{\frac{I_0}{K_2}}
\]
- For future reference: what if \( I_b \) had a small signal component \( \rightarrow \) what is current gain?

\[
\begin{align*}
V_b &= I_b \left( \frac{1}{g_{m1}} \right) \\
&\approx I_b \cdot \frac{1}{g_{m1}} \quad (\text{small})
\end{align*}
\]

\[
\begin{align*}
V_o &= g_{m2} V_b = \frac{g_{m2}}{g_{m1}} I_b = \frac{K_2}{K_1} I_b = \frac{(wK_2)}{(wK_1)} I_b
\end{align*}
\]

*Note: "i-mini" acts as a current mirror for DC \& AC when both active, neglecting 2.*

*How to improve \( R_{out} \), \( (V_o)_{min} \), matching 3.*

**Start with \( R_{out} \): try adding an external resistor, \( R_x \):

\[
\begin{align*}
V_{os} &= V_o - I_o R_x \quad \text{for active/sat: } V_{os} > V_{os1} \\
\Rightarrow V_o &= I_o R_x \quad \text{for } V_{os} > V_{os1} \\
\Rightarrow V_o &= I_o R_x + \sqrt{\frac{I_{os1}^2}{K_1}}
\end{align*}
\]
\[
\Rightarrow (V_0)_{\text{min}} = I_o R_x + \sqrt{\frac{I_o}{K_i}} \quad \text{显著更差于} \quad V_i \text{, 独立于 } R_i,
\]

\[
R_o > \frac{S}{SSM},
\]

\[
\begin{cases}
\sqrt{R_o} \\
R_x \\
R_dS_1
\end{cases}
\]

\[
R_o = R_x + R_dS_1
\]

- Place \( R_x \) at source instead; use \( R_s \):

- To achieve desired \( I_o, V_0 \) must be:
  - \( V_0 = I_o R_s + V_d + V_{0i} \)

- \((V_0)_{\text{min}} = I_o R_s + V_{0i} \) (same as \( \omega/R_x \))

- \( R_o = \frac{S}{SSM} \Rightarrow \text{use test source, } V_d \):

\[
SSM:
\]

\[
\begin{array}{c}
\begin{aligned}
V_{gs} &= -i_t R_s \\
V_i &= i_t R_s + (i_t + i_t R_s G_m) R_dS
\end{aligned}
\end{array}
\]

\[
\Rightarrow \frac{V_i}{i_t} = \frac{R_s + R_dS + G_m R_dS R_s}{\text{same as } R_x} \quad \text{"gain" of device (GmRdS) times } R_s!
\]
\[ R_o = R_s + R_{ds} + g_m R_s, \text{ } R_s \ll \ forbid \] 
\[ \text{ } g_m, R_{ds}, R_s, \text{ } R_s \text{ large} \]

- Why does \( R_s \) have so much larger effect over \( R_{ds} \)?

- Consider feedback from device: If there is a perturbation in \( I_o \): \( R_s \Rightarrow \frac{R_o}{R_s} \Rightarrow V_{gs} \Rightarrow \downarrow I_o \)

- \( V_{gs} \) feedback loop counters changes in \( I_o \) \( \Rightarrow \) increases \( R_o \)

- What about body effect? For nMOS, if body = 0 and source tied to \( R_s \) \( \Rightarrow V_{bs} \approx 0 \).

- in SS: \[
\begin{align*}
Gm &\quad Gm' &\quad Gmb &\quad V_{gs} \\
\downarrow &\quad \downarrow &\quad \downarrow &\quad \downarrow \\
Gm &\quad Gm' &\quad Gmb &\quad V_{gs}
\end{align*}
\]

- all else same except for addition of \( V_{bs} \)

- Note: since gate and body are both small, 
- since \( V_{gs} \approx V_{gs} \approx -I_b R_s \)

- \( V_{gs} = V_{bs} \)

- same result applies if we substitute: \( Gm' = Gm + Gmb = Gm (1 + R) \)

- Note: \( Gmb \) increases \( R_o \) by increasing \( Gm \) by \( \approx 20\% \)

- Why?: feedback again: \( R_s \Rightarrow \frac{R_o}{R_s} \Rightarrow V_{gs} \Rightarrow V_t \Rightarrow \downarrow I_o \)

- Still: large \( R_o \) requires large \( R_s \) \( \Rightarrow \) How to decrease \( (V_o)_{min} \)?