Problems with $R_s$ & $M$ as I-source:
- $I_0$ depends significantly on $R_s$ (this may be
  desired & exploited in some design, but is not
  good for basic matched current mirror)
- Poor $V_0 \min$ for large $R_s + I_0$

Desire an equivalently large small-signal resistance,
but with a small large-signal voltage drop.

- Use a mosfet in active:

- $M_2$ replaces $R_s$; if active, has
  equiv. small-signal $R_s = R_{ds2}$
- $M_1$ & $M_3$ are one simple option
  to bias $V_{ds1} + V_{ds2}$ such that
  all devices are active (for $V_0 \gg V_0 \min$)
  and $M_1$ & $M_2$ form a I-mirror.

- $I_0 \approx \frac{g_m}{g_m} \frac{I_0}{I_0}$ for $V_0 \gg V_0 \min$

- $R_0 = R_{ds1} + R_{ds2} + \frac{g_m}{g_m} R_{ds1} R_{ds2} \approx \frac{g_m}{g_m} R_{ds1} R_{ds2}$

- $V_{0 \min} = \text{biad of } M_1 = V_{ds1} + V_{ds2} = V_{ds1} + V_3$

- If $\frac{K_2}{K_1} = \frac{K_4}{K_3}$ \( \Rightarrow \)
  $V_2 = V_{ds1} = V_{ds1,2} = V_4 + V_{ds2}$
(V_o)_{\text{min}} = V_{ou1} + V_{ou2} + V_e
\text{controlled by size/design}
\text{process parameter} \Rightarrow \text{fixed}
V_o = \frac{I_o}{\sqrt{K}}

\Rightarrow \text{Thus, (V_o)_{min} can be close to } V_o \text{ for large M2 from, which is a significant improvement over using a few MR Rs (e.g. MR=R, ZouA \Rightarrow 20V!)}

\text{Note: (V_o)_{min} is the lower limit to maintain the spec. I_o \& R_o. In this case, for } V_o \text{ just below (V_o)_{min}, M1 \rightarrow triode, but M2 is still active. Further decrease in } V_o \text{ will cause a decrease in } V_3 \text{ (since M4 acts as a small resistor). At } V_o \approx V_{ou2} \Rightarrow M2 \rightarrow \text{triode & I_o will begin to significantly deviate from ideal.}

\text{From: } V_{ou2} < V_o < (V_o)_{\text{min}} \Rightarrow M4: \text{triode}
M1 & M2: \text{active, circuit behaves like a simple I-mirror w/ M1 \& M2 (without M3 \& M4)}: R_o \approx \frac{R_o}{R_o S_2}

\text{For } V_o > (V_o)_{\text{min}} + R_o \approx \frac{R_o}{R_o S_2} \Rightarrow \text{the circuit is considered a "cascoded" I-mirror/I-source.}
The cascade F-source has a very large peak + reasonable \( V_{o\min} \). However, we can do better by adjusting \( V_{b2} \) to remove the fixed term \( V_{t} \) from \( V_{o\min} \):

$$ V_{b2} = \frac{I_o}{15M_2} $$

- design \( V_{b1} \) for desired \( I_o \) using \( I_{min} \)

- what is \( \min V_{b2} \) to be maintain \( I_o \)?

\[ \Rightarrow \text{need } M_2 : \text{active } S_e \Rightarrow \text{stay out of triode.} \]

Limit is: \( V_3 = V_{o2} \Rightarrow V_{b2} = V_{o2} + V_{b3y} \)

\( (V_{b2})_{min} = V_{o2} + V_{b3y} + V_{t4} \)

which may include body effect!

\( @ (V_{b2})_{min}, V_3 = V_{o2} + (V_0)_{min} = V_{b3y} + V_{o2} = \text{Two over-drives.} \)

\( \Rightarrow \text{Thus, } (V_0)_{min} \text{ can be made very small for } \)

\( \text{large } K_2 + K_4 \text{ or small } I_o \).

\( \text{How to realize } (V_{b2})_{min} ? \Rightarrow \text{many options with } \)

\( \text{various limitations on currents, device sizes, } + \)

\( \text{power loss.} \)
- Straightforward approach: use separate bias.

- Neglecting body effect: \( V_{t3} = V_{t4} \) \( \Rightarrow V_{o3} = V_{o2} + V_{o4} \)

- If \( k_2 = k_4 \) (same size) \( \Rightarrow V_{o2} = V_{o4} \) \( \Rightarrow V_{o3} = 2V_{o2,4} \)

\[ \Rightarrow \frac{I_b}{K_3} = 4 \cdot \frac{I_o}{K_4} \Rightarrow \frac{K_3}{K_4} = \frac{1}{4} \cdot \frac{I_b}{I_o} \]

\[ \uparrow \quad \uparrow \]

Scale \( V_{t4} \) \( \quad \) Current ratio

to remove \( V_t \) from \( (V_0)_{min} \).

- In practice, a slightly smaller scale factor is generally used (larger \( M_3 \)) to increase \( V_3 \) \( (V_0)_{min} \)

\[ \uparrow \quad \uparrow \]

to move \( M_2 \) deeper into active/sat (for margin from triode).