To achieve high gain (or low attenuation in the case of a source follower), it is very desirable to achieve high load impedance, $Z_L$.

- Unfortunately, using a simple resistor of high value has issues:
  - What are these issues?
Issue: Headroom Limitations

The bias current of the device is a direct function of $R_L$

$$I_d = \frac{V_{dd} - V_{ds}}{R_L}$$

- $V_{dd}$ is $< 3.6V$ for most modern CMOS processes
- $V_{ds}$ must be greater than $\Delta V$ to maintain device saturation

Large $R_L$ implies small $I_d$
(implies small $g_m$, poor frequency response, etc.)
Achieving High Gain

- Replacement of resistor load with a current source yields the highest possible DC gain out of the amplifier
  - Current source determines $I_d$ of device
- We can make current sources out of transistors
  - Generally smaller area than polysilicon resistors

What is the small signal gain of the above circuit?
• How do we build current sources?
• Let’s start with a “diode connected” device
• A MOS device with gate and drain shorted operates like a diode (but not exponential)
• We can derive the small-signal model by shorting out the hybrid-pi model

• Note that a Gm generator with it’s controlling terminals connected to the Gm is more simply a …?
The Integrated “Current Mirror”

- M₁ and M₂ have the same V_{GS}
- If we neglect CLM (\lambda=0), then the drain currents are equal
- Since \lambda is small, the currents will nearly mirror one another even if V_{out} is not equal to V_{GS₁}
- We say that the current I_{REF} is mirrored into i_{OUT}
- Notice that the mirror works for small and large signals!
Multiplication Ratio

\[ I_{\text{IN}} = k \frac{W_1}{L_1} (V_{GS1} - V_T)^2 \]

\[ V_{GS2} = \frac{2}{k} \frac{V_{\text{in}}}{W} + V_{TH} \]

\[ I_{\text{OUT}} = k \frac{W_2}{L_2} (V_{GS2} - V_T)^2 \]

\[ I_{\text{OUT}} = N \frac{W_1}{L_1} (V_{GS1} - V_{TH})^2 \]

\[ \frac{I_{\text{OUT}}}{I_{\text{IN}}} = N \]

\[ N = \frac{(W/L)_2}{(W/L)_1} \]
Current Mirror as Current Source

- The output current of M₂ is only weakly dependent on v_{OUT} due to high output resistance of FET
- M₂ acts like a current source to the rest of the circuit
- For good current source behavior, what is the minimum v_{OUT}?
Small-Signal Resistance of $I$-Source

\[ i' = \frac{V_t}{R_0} \]

\[ I_{eq} = \frac{v_{gs}}{g_m} \]

\[ r_o \]

Cal
Improved Current Sources

Goal: increase $R_{o(ut)}$

Approach: look at amplifier output resistance results … to see topologies that boost resistance

Looks like the output impedance of a common-source amplifier with source degeneration
Effect of Source Degeneration

- Equivalent resistance loading gate is dominated by the diode resistance ... assume this is a small impedance

- Output impedance is boosted by factor \((1 + g_m R_S)\)

\[
\begin{align*}
v_t &= (i_t - g_m v_{gs})r_o + v_{R_S} \\
v_{gs} &\approx -v_{R_S} \\
v_{R_S} &= i_t R_S \\
v_t &= (i_t + g_m R_S i_t)r_o + i_t R_S \\
R_o &= \frac{v_t}{i_t} \approx (1 + g_m R_S) r_o
\end{align*}
\]
Improved Current Sources

How would you scale the output current?

\[ I_{IN} = k \frac{W_1}{L_1} (V_G - V_S - V_T)^2 \]

\[ V_S = I_{IN} R_S \]
Cascode (or Stacked) Current Source

Insight: \( V_{GS2} = \text{constant AND} \)
\( V_{DS2} = \text{constant} \)

Small-Signal Resistance \( R_o \):

\[
R_o \approx \left(1 + g_m R_S\right) r_o
\]
\[
R_o \approx \left(1 + g_m r_o\right) r_o
\]
\[
R_o \approx g_m r_o^2 \gg r_o
\]
Drawback of Cascode \( I \)-Source

What is the minimum output voltage to keep all transistors in saturation?

\[ V_{\text{out}, \text{min}} = V_{\text{ref}} - V_T \]

Better impedance performance

Worse headroom:

\[ V_{\text{out}, \text{min}} = V_{DD} + V_{\text{ref}} - V_T \]
Drawback of Cascode $I$-Source

Minimum output voltage to keep both transistors in saturation:

$$V_{OUT, MIN} = V_{DS4, MIN} + V_{DS2, MIN}$$

$$V_{DS2, MIN} > V_{GS2} - V_{T0} = V_{DSAT2}$$

$$V_{D4} > V_{DSAT2} + V_{GS4} = V_{GS2} + V_{GS4} - V_{T0}$$

In EE140 you will learn circuit tricks to overcome this problem!
Current Sinks and Sources

**Sink**: output current goes to ground

**Source**: output current comes from voltage supply

\[ I_{in} \downarrow \]
\[ V_{gs1} \]
\[ + \]
\[ V_{gs2} \]
\[ + \]
\[ V_{out} \]
\[ - \]
\[ \downarrow I_{out} \]

\[ V_{DD} \]

\[ \downarrow \]
\[ I_{ref} \]
\[ \downarrow \]

\[ I_{out} \]

\[ \downarrow \]

\[ I_{out} \]

\[ \downarrow \]

\[ I_{out} \]

\[ \downarrow \]
**Current Mirrors**

*Idea*: we only need one reference current to set up all the current sources and sinks needed for a multistage amplifier.
Example: Common-Drain Amplifier

\[ I_{DS} = \mu C_{ox} \frac{W}{L} \frac{1}{2} (V_{GS} - V_{T})^2 \]
How does a REAL current source fit in to the small-signal model?
CD Voltage Gain With Real I-Source

**Ideal I-Source**

\[
\frac{V_{out}}{R_L || r_o} = g_m v_{gs}
\]

\[
V_{out} = g_m v_{gs} \cdot \frac{R_L || r_o}{r_o}
\]

\[
\frac{v_{out}}{R_L || r_o} = g_m (V_{in} - V_{out}) \cdot R_L || r_o
\]

**Real I-Source**

\[
V_{out} = g_m v_{gs} \cdot \left[ R_L || r_o || r_{2o} \right]
\]
CD Voltage Gain (Cont.)

KCL at source node:

Voltage gain:

\[
\frac{v_{out}}{v_{in}} = \frac{g_m}{g_m + \frac{R_{L}||R_{L,ref}}{}},
\]

\[
v_{out} = g_m (v_{in} - v_{out}) = 0,
\]

\[
R_{L}||R_{L,ref} = R_{L}||R_{L,ref}.
\]