Passive Loads vs Active Loads

- MOS diff amp loads are generally transistors on ICs

For the same $\Delta I_D$ active load yields more voltage swing: it has a bigger dynamic resistance.

Be careful to keep active load in saturation!!
Active Loads

- MOS diff amp loads are generally transistors in ICs

Just like in BJT ICs!

\[ g_m = \frac{I}{V_{GS} - V_t} \]

\[ i = g_m \frac{v_{id}}{2} \]

\[ v_o = 2i(r_{o2} \parallel r_{o4}) \]

\[ v_o = g_m v_{id} (r_{o2} \parallel r_{o4}) \]

\[ \therefore A_v = g_m (r_{o2} \parallel r_{o4}) \]

What if we add a next stage? What is \( R_{in} \)?
Two Stage OpAmp

Given $I_{\text{ref}}$ solve for $g_m$’s

$g_{m1} = 64.1 \mu A/V$

$g_{m6} = 111 \mu A/V$

$r_{o2} = V_A/I_D = 1.82 \text{M} \Omega = r_{o4}$

$r_{o6} = 0.813 \text{M} \Omega = r_{o7}$
Two Gain Stages

Diff. gain:

\[ A_{\text{diff}} = g_m (r_{o2} \| r_{o4}) \]
\[ A_{\text{diff}} = 64 \frac{\mu A}{V} \left( \frac{1.82 \, m\Omega}{2} \right) = 58.3 \frac{V}{V} \]

Commen source gain:

\[ A_2 = -g_m (r_{o6} \| r_{o7}) \]
\[ A_2 = -45.1 \frac{V}{V} \]
Two Stage OpAmp

- The overall gain is the product of the two stage gains

\[ |A_1A_2| = \left| -2629 \frac{V}{V} \right| = 68.4\, dB \]

roll-off due to gate input capacitances
Compensation

compensation between diff and high gain stage
**Common Gate Configuration**

What is $r_{in}$?

$$v_x = -v_{gs}$$

$$r_{in} = \frac{v_x}{i_x} = \frac{(R_L + r_o)}{r_og_m}$$

For $R_L \ll r_o$:  

$$r_{in} = \frac{1}{g_m}$$

What is $r_{out}$?

$$r_{out} = r_o$$

What is current gain?

$$A_i \approx 1$$

Why not $=$?

Leakage currents from DB, SB diodes

What is voltage gain?

$$A_V < 1$$

Note: we neglect $g_{mb}$ here
Common Gate Configuration

- Common gate configuration acts as a current buffer (just like common base)

![Diagram of a common gate configuration with small $r_{in}$ and huge $r_{out}$]
**Cascode**

- Cascade of common source and common gate stages.
- Broader frequency band than common source
- Higher output impedance than common source

Broader frequency band is due to limited Miller effect

\[
A_v = -g_m (R_L \parallel r_{o1})
\]

...but Cascode makes \(R_L\) small (as seen by the common source stage) so that \(A_v\) is small. So, Miller effect on M1 is minimized. Voltage gain of the cascode is obtained by adding load resistor on output of the common gate connected M2.
Cascode - increased output impedance

\( r_{out} = \)

\[ v_x = i_x r_{o1} + (i_x - g_m v_{gs2}) r_{o2} \]

\[ v_x = i_x r_{o1} + (i_x + g_m i_x r_{o1}) r_{o2} \]

\[ r_{out} = \frac{v_x}{i_x} = r_{o1} + r_{o2} + g_m r_{o1} r_{o2} \approx g_m r_{o1} r_{o2} \]

In comparison with \( r_{o1} \), \( r_{out} \) is increased by factor \( g_m r_{o2} \) (typically: 20-100)
Cascode current source - increased output impedance

\[ r_{out} = g_m r_{o1} r_{o2} \]

Problem with this circuit: lower range of output voltage signal swing:
need at least approx \( 2 \times V_{DS \text{ Sat}} \) on output
Problem from previous year’s exam#3

Calculate the midband gain \( \left( \frac{v_o}{v_1 - v_2} \right) \) as a function of I (the reference current) for the two-stage CMOS opamp shown below. Assume that all of the biasing is working properly. Show all of your work!

\[
\begin{align*}
\lambda_p &= 0.02 \\
\lambda_n &= 0.01 \\
\mu_p C_{ox} &= 20 \mu A/V^2 \\
\mu_n C_{ox} &= 20 \mu A/V^2
\end{align*}
\]

1. Calculate currents of M5 and M8
2. Calculate gain \( A_{\text{diff}} \) of the differential stage M5-M1-M2-M3--M4
3. Calculate gain \( A_2 \) of the second stage
4. Combine \( A_{\text{diff}} \) and \( A_2 \)
1. Calculate currents of M5 and M8

Calculate the midband gain \( \frac{v_o}{(v_1 - v_2)} \) as a function of \( I \) (the reference current) for the two-stage CMOS opamp shown below. Assume that all of the biasing is working properly. Show all of your work!

\[
\begin{align*}
\lambda_p &= 0.02 \\
\lambda_n &= 0.01 \\
\mu_p C_{ox} &= 20 \mu A/V^2 \\
\mu_n C_{ox} &= 20 \mu A/V^2
\end{align*}
\]

Assume that the influence of different \( V_{DS} \) of M6, M5 and M8 on current matching is negligible.

\[
I_{D5} = I \left( \frac{W_5}{L_5} \right) = 4I \\
I_{D8} = 4I
\]
2. Calculate gain $A_{\text{diff}}$ of the differential stage M5-M1-M2-M3--M4

Calculate the midband gain ($v_o/(v_1-v_2)$) as a function of $I$ (the reference current) for the two-stage CMOS opamp shown below. Assume that all of the biasing is working properly. Show all of your work!

\[
\begin{align*}
\lambda_p &= 0.02 \\
\lambda_n &= 0.01 \\
\mu_p C_{ox} &= 20\mu A/V^2 \\
\mu_n C_{ox} &= 20\mu A/V^2
\end{align*}
\]

We neglect body effect on M1 and M2

\[
A_{\text{diff}} = g_m (r_{o2} \parallel r_{o4})
\]

\[
g_m = \sqrt{2\mu_n C_{ox}} \sqrt{\frac{W}{L}} \sqrt{I_D}
\]

\[
g_m = \sqrt{2 \times 20e - 6 \times 10} \times 1 = 0.02 \sqrt{2I} \text{[S]}
\]

\[
r_{o2} = \frac{1}{2I\lambda_n} = \frac{50}{I} \text{[}\Omega\text{]}
\]

\[
r_{o4} = \frac{1}{2I\lambda_p} = \frac{25}{I} \text{[}\Omega\text{]}
\]

\[
A_{\text{diff}} = 0.02 \sqrt{2I} \left(\frac{16.666}{I}\right)
\]
3. Calculate gain of the second stage

Calculate the midband gain \( \frac{v_o}{(v_1 - v_2)} \) as a function of I (the reference current) for the two-stage CMOS opamp shown below. Assume that all of the biasing is working properly. Show all of your work!

\[
\begin{align*}
\lambda_p &= 0.02 \\
\lambda_n &= 0.01 \\
\mu_p C_{ox} &= 20\mu A/V^2 \\
\mu_n C_{ox} &= 20\mu A/V^2
\end{align*}
\]

Common Source amplifier

\[
A_2 = -g_m 7 (r_{o7} \parallel r_{o8})
\]

\[
g_m = \sqrt{2\mu_p C_{ox} \frac{W}{L} \sqrt{I_D}}
\]

\[
g_m = \sqrt{2 \times 20e - 6 \times 15 \sqrt{4I}} \approx 0.05 \sqrt{I} [S]
\]

\[
r_{o8} = \frac{1}{4I\lambda_n} = \frac{25}{I} [\Omega]
\]

\[
r_{o7} = \frac{1}{4I\lambda_p} = \frac{12.5}{I} [\Omega]
\]

\[
A_2 = -0.05 \sqrt{I} \left( \frac{8.333}{I} \right)
\]
4. Combine gain of both stages

Calculate the midband gain \( \frac{v_o}{(v_1-v_2)} \) as a function of \( I \) (the reference current) for the two-stage CMOS opamp shown below. Assume that all of the biasing is working properly. Show all of your work!

\[
\lambda_p = 0.02 \\
\lambda_n = 0.01 \\
\mu_p C_{ox} = 20 \mu A/V^2 \\
\mu_n C_{ox} = 20 \mu A/V^2
\]

\[A_{diff} = 0.02 \sqrt{2I} \left( \frac{16.666}{I} \right)\]

\[A_2 = (-0.05) \sqrt{I} \left( \frac{8.333}{I} \right)\]

\[A_v = A_{diff} A_2 \approx -\frac{0.2I}{V} \]