Announcements

- Homework 6 due next Tuesday
- Lab 4 this week
- Reading: Chapters 9.4, 8 (MOS only)
- Midterm 1 next week
  - October 13, 6:30-8pm, Sibley
- Review session on Tuesday
  - October 11, 6:30-8pm, 277 Cory
Lecture Material

- Last lecture
  - MOSFET small-signal model
- This lecture
  - MOS current sources
  - Generalized two-port models

Application of Current Mirrors:
Digital-to-Analog Converter

Digital input: word $D_0D_1D_2D_3$ → voltages are either $V_{DD}$ or 0 V.
Transistors $M_0, M_1, M_2, M_3$ have binary-weighted ($W/L$) ratios
Example

Input word $D_0D_1D_2D_3 = 0101$

$I_{\text{REF}} = 100 \ \mu\text{A}$

$(W/L)_{\text{REF}} = (W/L)_0$
$(W/L)_1 = 2(W/L)_0$
$(W/L)_2 = 2(W/L)_1$
$(W/L)_3 = 2(W/L)_2$

Output voltage is $v_{\text{OUT}} = V_{\text{DD}} - R_L(i_{D0} + i_{D2})$

$= V_{\text{DD}} - R_L(I_{\text{REF}} + 4I_{\text{REF}})$

Sources of error: fab imprecision, channel-length modulation, ...

Generalized Amplifier

The diagram shows a generalized amplifier with input $v_{\text{in}}$, output $v_o$, bias voltage $V_{\text{BIAS}}$, and active device $I_{\text{DD}}$. The equations $i_D = f(v_{\text{in}})$ and $i_L = I_{\text{DD}} - i_D$ are also shown.
Amplifier Terminology

- **Sources**: Signal, its source resistance, and bias voltage or current
- **Load**: Use resistor/current source or in Chap. 8, but could be a general impedance
- **Port**: A pair of terminals across which a voltage and an associated current are defined

- Source, Load: “one port”
- Amplifier: “two port”

One-Port Models (EECS 40)

- A terminal pair across which a voltage and associated current are defined
We assume that input port is linear and that the amplifier is unilateral:

- Output depends on input but input is independent of output.
- Output port: depends linearly on the current and voltage at the input and output ports
- Unilateral assumption is good as long as “overlap” capacitance is small (MOS)
Math 54 Perspective

Can write linear system of equations for either $i_{out}$ or $v_{out}$ in terms of two of $i_{in}$, $v_{in}$, $i_{out}$, or $v_{out}$: possibilities are

\[
\begin{align*}
    i_{out} &= \alpha_1 v_{in} + \alpha_2 v_{out} \\
    i_{out} &= \alpha_3 i_{in} + \alpha_4 v_{out} \\
    v_{out} &= \alpha_5 v_{in} + \alpha_6 i_{out} \\
    v_{out} &= \alpha_7 i_{in} + \alpha_8 i_{out}
\end{align*}
\]

What is physical meaning of $\alpha_1$? of $\alpha_6$?

EE Perspective

- Four amplifier types: determined by the output signal and the input signal ... both of which we select (usually obvious)
  - Voltage Amp ($V \rightarrow V$)
  - Current Amp ($I \rightarrow I$)
  - Transconductance Amp ($V \rightarrow I$)
  - Transresistance Amp ($I \rightarrow V$)
- Need methods to find the 6 $\alpha$ parameters for the four models and equivalent circuits for unilateral two ports
Two-Port Small-Signal Amplifiers

Voltage Amplifier

Current Amplifier

Transconductance Amplifier

Transresistance Amplifier
**Input Resistance $R_{in}$**

Looks like a Thevenin resistance measurement, but note that the output port has the load resistance attached.

\[ R_{in} = \left. \frac{v_t}{i_t} \right|_{R_S \text{removed}, \ R_L \text{attached}} \]

\[ \text{Two-Port Amplifier} \]

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**Output Resistance $R_{out}$**

Looks like a Thevenin resistance measurement, but note that the input port has the source resistance attached.

\[ R_{out} = \left. \frac{v_t}{i_t} \right|_{R_L \text{removed}, \ R_S \text{attached}} \]

\[ R_S \]

\[ \text{Two-Port Amplifier} \]
Finding the Voltage Gain $A_v$

Key idea: the output port is open-circuited and the source resistance is shorted

$$A_v = \frac{v_{out}}{v_{in}} \bigg|_{R_S = 0, R_L \to \infty}$$

Finding the Current Gain $A_i$

Key idea: the output port is shorted and the source resistance is removed

$$A_i = \frac{i_{out}}{i_{in}} \bigg|_{R_S \to \infty, R_L = 0}$$
Finding the Transresistance $R_m$

$$R_m = \left. \frac{v_{out}}{i_{in}} \right|_{R_s \to \infty, R_L \to \infty}$$

Finding the Transconductance $G_m$

$$G_m = \left. \frac{i_{out}}{v_{in}} \right|_{R_s = 0, R_L = 0}$$
Common-Source Amplifier (again)

How to isolate DC level?

DC Bias

Neglect all AC signals

Choose $I_{BIAS}$, $W/L$
**Load-Line Analysis to find $Q$**

\[ I_{R_D} = \frac{V_{DD} - V_{out}}{R_D} \]

\[ I_D = \frac{5V}{10k} \]

\[ V_{BIAS} \text{ (V)} \]

\[ \text{slope} = \frac{1}{10k} \]

**Small-Signal Analysis**

\[ R_{m} = \infty \]

\[ + v_{gs} \]

\[ - \]

\[ g_m v_{gs} \]

\[ r_e \]
Two-Port Parameters:

Find $R_{in}$, $R_{out}$, $G_m$

$R_s$

Generic Transconductance Amp

$G_m = g_m$  $R_{out} = r_o \parallel R_D$

Two-Port CS Model

Reattach source and load one-ports: