Lecture 2
Preliminary for Analog IC Design

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Outline

- Reference books on opamp circuit design
- Building block cells for analog IC
- Transistor model and basic design equations
- Circuit simulation (recommended simulators)

Textbooks (Recommended)

1. D.A. Johns and K. Martin, Analog Integrated Circuit Design, NY, Wiley, 1997.
2. B. Razavi, Design of Analog CMOS Integrated Circuits, McGraw Hill, 2001.
3. P.E. Allen and D.R. Holberg, CMOS Analog Circuit Design, 2^{nd} Ed., NY, Oxford university Press, 2002.

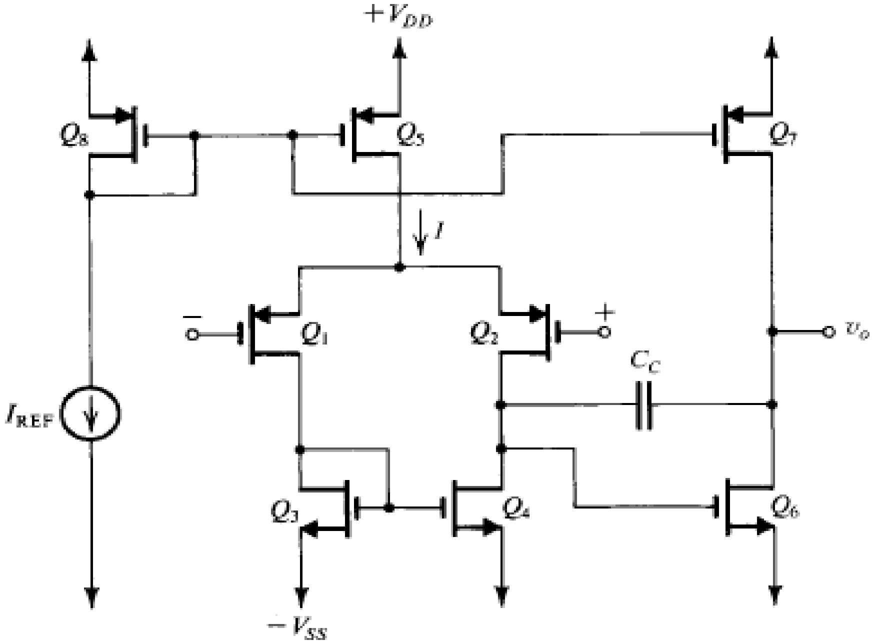
You may find the basic amplifier design information in these popular textbooks.

More Advanced Research Books

For more advanced materials, you may refer to the following books.

1. **R. Hogervorst, and J.H. Huijsing, Design of Low-voltage, Low-power Operational Amplifier Cells, Kluwer, 1996.**
2. **K.-J. de Langen, and J.H. Huijsing, Compact Low-voltage and High-speed CMOS, BiCMOS and Bipolar Operational Amplifiers, Kluwer, 1999.**
3. **J. H. Huijsing, Operational Amplifiers, Kluwer, Boston, 2001.**
4. **V. V. Ivanov, I. M. Filanovsky, Operational Amplifier Speed and Accuracy Improvement, Kluwer, Boston, 2004 (folded cascode and current mirror improvements using current amplifiers)**

A Basic Opamp



- **Differential PMOS input, single output**
- **Miller compensation**

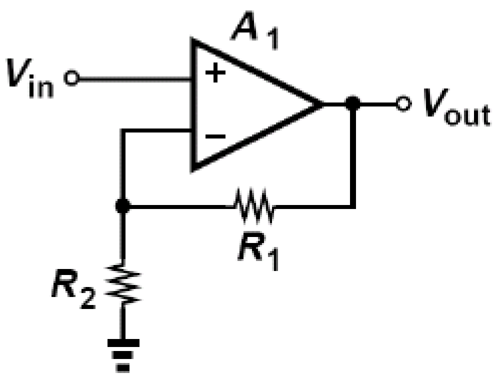
Circuit Basics

- **A basic opamp includes**
  - **Biasing circuit**
  - **Input stage (differential PMOS transistor stage with differential to single ended conversion, and output stage.**
  - **Compensation capacitor *Cc*, and**

- **The basic parameters of this amplifier:**
  - **DC gain**
  - **Bandwidth**
  - **Slew-rate (SR)**
  - **Offset and noise referred to the input.**

Opamps

- **Loosely an opamp is a "high-gain operational amplifier".**
- **By "high", we mean a value anywhere between 10 to 10^5 (100dB).**
- **Opamps are usually used in a feedback system, when an operation must be performed precisely.**



Ideal Opamp

- A_V = inf, R_{in} = inf, R_{out} = 0
- without considering: **power, output swing, and speed.**
- **Modern opamps are designed for a specific application,**
  - **often trading unimportant aspects for the important ones.**
- **e.g., most of today's CMOS opamps have a high output impedance (in open loop)**
  - **for supplying a current to the load**
- **they are often called "transconductance amplifiers"**
  - **i.e. voltage-to-current amplifier (like the effect of gm)**

Typical Performance Metrics

- **Gain, speed, output swing, linearity, power dissipation;**
- **Noise, input CM range, supply rejection;**
- **Input offset voltage V_{OS};**
- **etc.**

- **All these metrics are related to the transistor-level details.**

Building Blocks (Cells)

Cell-based Design

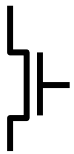
- **Just like the design of other electronic circuits,**
- **the design of opamps can be greatly accelerated if we use a library of simple circuits, sometimes called cells.**

- **Cell-based design is also a fundamental idea for analog/mixed-signal design automation.**

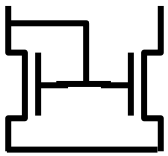
Typical Analog Modules

- **Operational amplifiers (opamps, V-to-V, V-to-I);**
- **OTA - Operational Transconductance Amplifiers (V-to-I);**
- **Comparators (in ADC);**
- **Oscillators (in RF frontend);**
- **Voltage references (bandgap)**
- **Temperature compensation**
- **Current references**
- **DC-DC (voltage regulation)**
- **...**
- **Each requiring special design expertise**

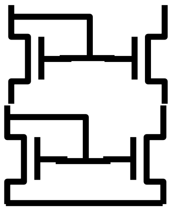
Example: Basic Analog Building Blocks



Single transistor (g_m)

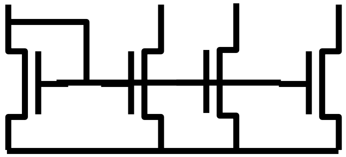


Simple **current mirror**



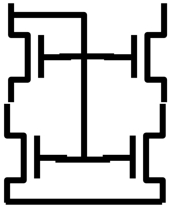
Cascode **current mirror**

(for higher output impedance)



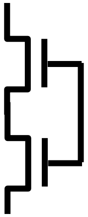
Current mirror bank

(for current-mode design)



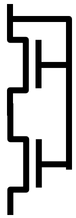
4-transistor **current mirror**

(for wide swing)

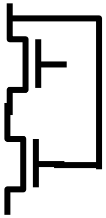


Load to current mirror

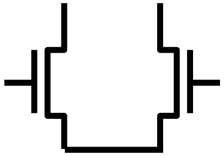
Building Blocks (cont'd)



Voltage reference 1

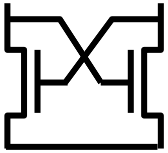


Voltage reference 2



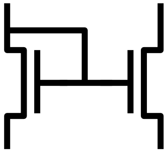
Differential pair

(input)

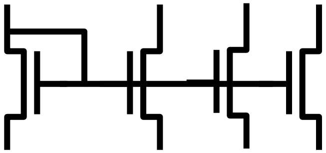


Flip-Flop

(bistable circuit)



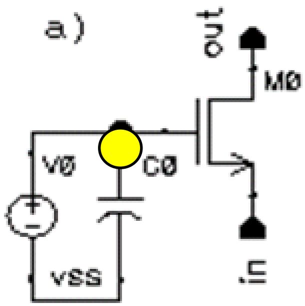
Level shifter



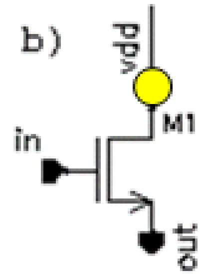
Level shifter bank

T. Massier, H. Graeb, U. Schlichtmann, "The sizing rules method for CMOS and bipolar analog integrated circuit synthesis," *IEEE Trans. on CAD*, vol. 27, no. 12, pp. 2209 – 2222, 2008.

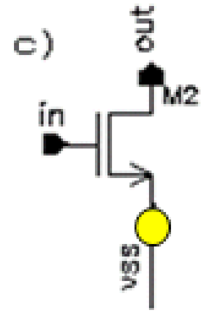
Traditional Cells



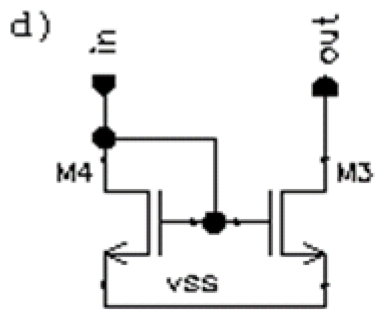
Common gate
(Gate signal not varying)



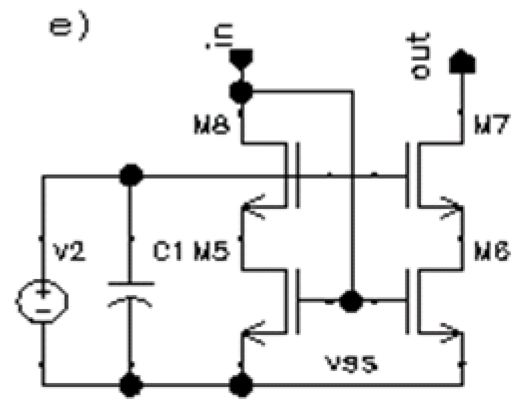
Common drain
(Drain signal not varying)



Common source
(Source signal not varying)

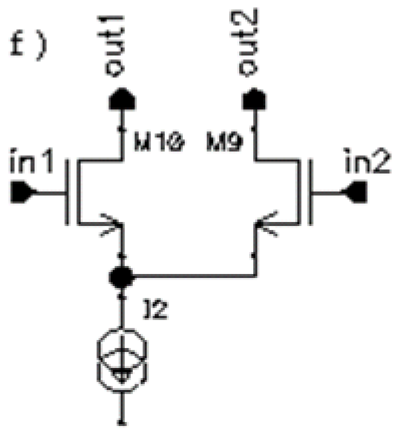


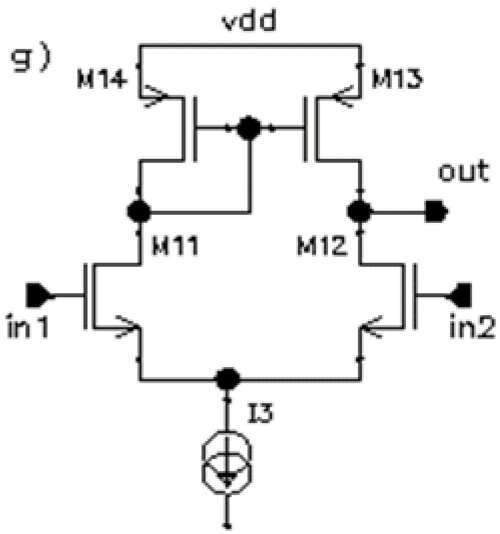
Simple current mirror



Cascoded current mirror

Traditional Cells (cont'd)





Differential pair (differential transconductance amplifier with current as output)

Differential pair with differential input and single-ended output

Ambitious Design Goals

Four one-hundreds:

By modifying the basic structure, one can achieve the following performance :

- **100 dB gain, (= 10^5)**
- **100 dB CMRR, and**
- **100 dB PSRR.**

The obtained amplifier has input and output rail-to-rail operation, and is compensated for 100% feedback operation (operating signal range).

Basic Design Equation (I-V)

$$I_D = \frac{\beta}{2}\left[2(V_{GS} - V_T) - V_{DS}\right]V_{DS};$$

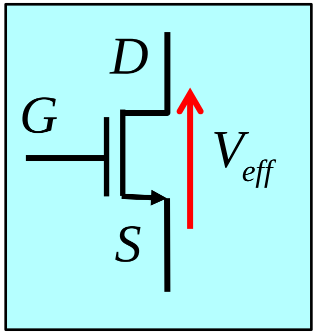
$$\beta := \mu C_{ox}\frac{W}{L} = K_{n,p}\frac{W}{L}$$

$$K_{n,p} = \mu C_{ox}$$

$$V_{DS} = (V_{GS} - V_T) \triangleq V_{eff}$$

$$I_D = \frac{\beta}{2}(V_{GS} - V_T)^2 = \frac{\beta}{2}(V_{eff})^2$$

$$g_m = \frac{\partial I_D}{\partial V_{eff}} = \beta V_{eff} = \sqrt{2\beta I_D} = \sqrt{2K_{n,p}\frac{W}{L}I_D}$$

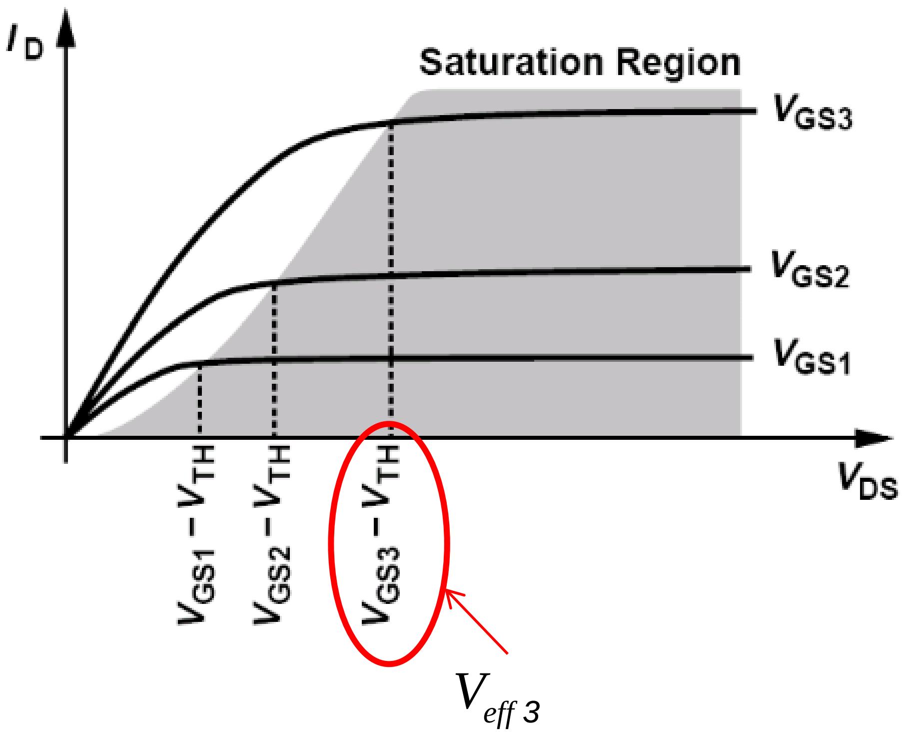


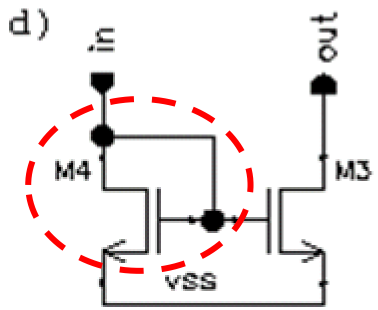
$$\frac{W}{L} = \frac{g_m^2}{2KI_D}$$

g_m and I_D determine the size ratio

$$K = K_{n,p}$$

MOS Current-Voltage Characteristics





That's why diode connected MOS works in saturation.

When $V_{DS} \geq V_{eff}$, I_D is in saturation.

$$V_{DS} = V_{GS} \geq V_{GS} - V_T = V_{eff}$$

Circuit Simulation

- **I assume all students have experience on HSPICE, at least on PSPICE.**
- **HSPICE tutorial**
- **PSPICE tutorial (www.orcad.org)**
- **LTspice (www.linear.com)**
  - **A simulator by Linear Technology Corp**
  - **PC version available (download and install by yourself)**
  - **With mixed-signal functionality**

Reference

- **I. M. Filanovsky's tutorial slides on MWSCAS 2011.**