LECTURE 01 - INTRODUCTION TO CMOS ANALOG CIRCUIT DESIGN

LECTURE ORGANIZATION

Outline

- Introduction
- What is Analog Design?
- Skillset for Analog IC Circuit Design
- Trends in Analog IC Design
- Notation, Terminology and Symbols
- Summary

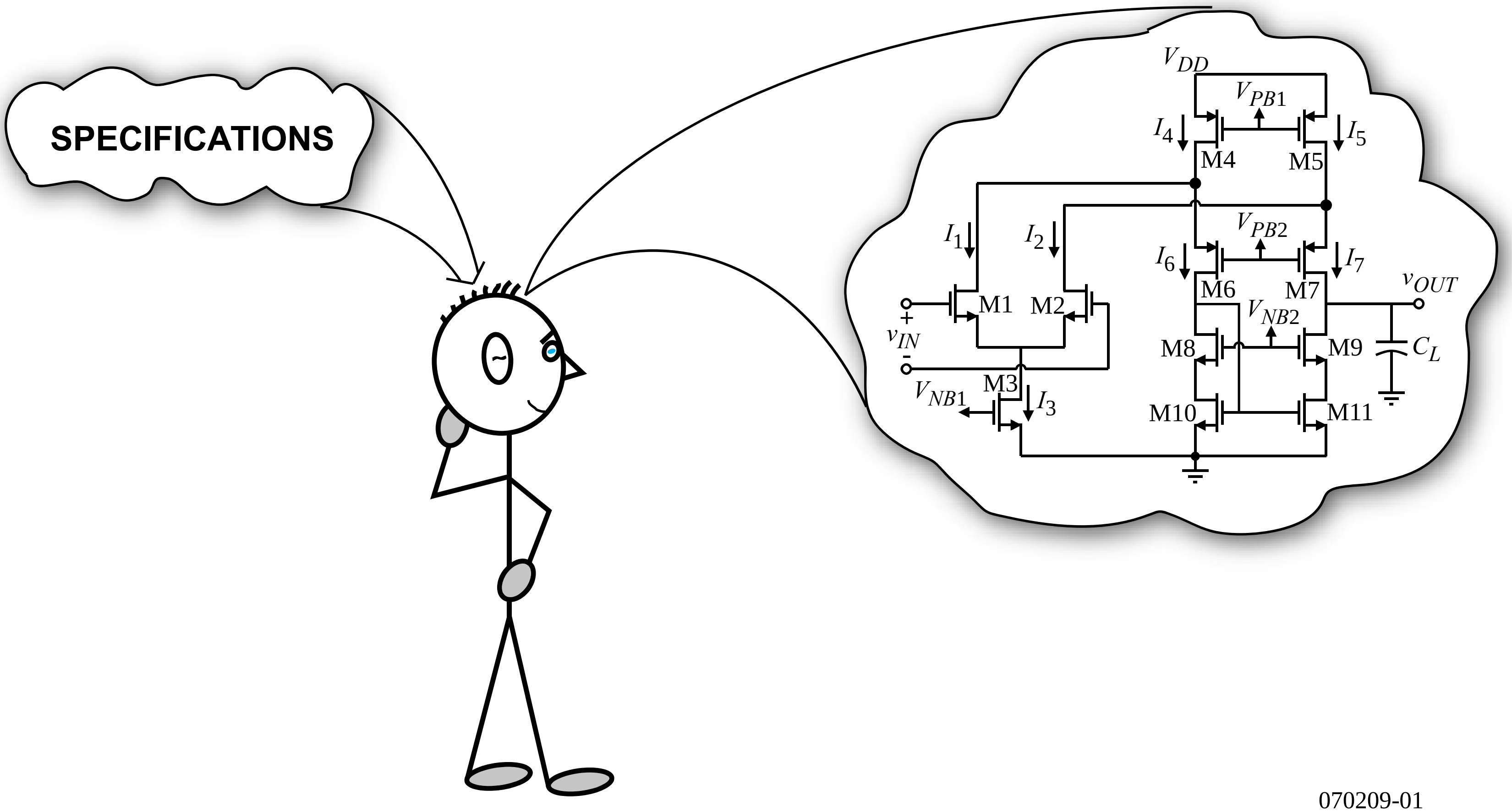
***CMOS Analog Circuit Design*, 3rd Edition Reference**

Pages 1-16

INTRODUCTION

Course Objective

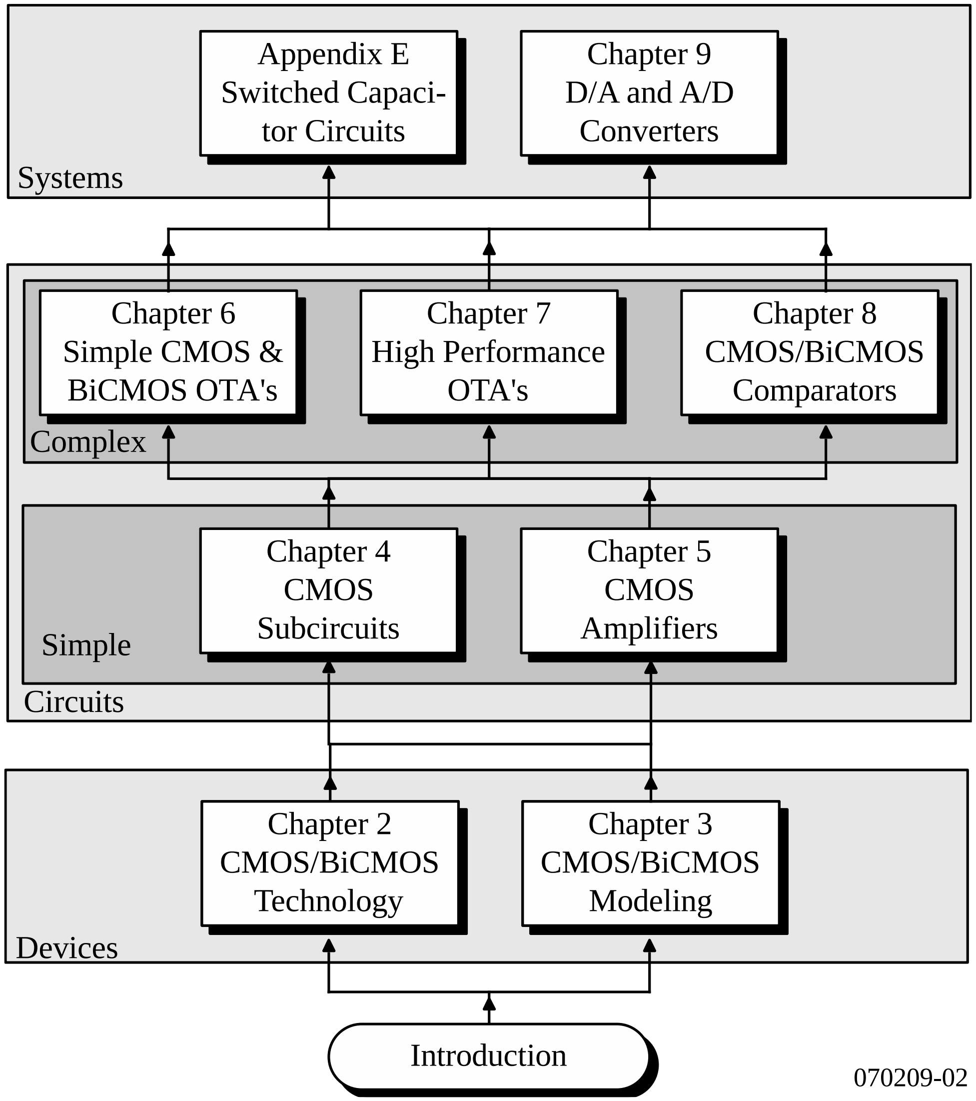
This course teaches analog integrated circuit design using CMOS technology.



Course Prerequisites

- Basic understanding of electronics
    - Active and passive components
    - Large and small signal models
    - Frequency response
- Circuit analysis techniques
    - Mesh and loop equations
    - Superposition, Thevenin and Norton's equivalent circuits
- Integrated circuit technology
    - Basics process steps
    - PN junctions

Course Organization – Based on 3rd Ed. of CMOS Analog Circuit Design



References

1.) P.E. Allen and D.R. Holberg, *CMOS Analog Circuit Design* – 3rd Ed., Oxford University Press, 2012.

2.) P.R. Gray, P.J. Hurst, S.H. Lewis and R.G. Meyer, *Analysis and Design of Analog Integrated Circuits* – 4th Ed., John Wiley and Sons, Inc., 2001.

3.) B. Razavi, *Design of Analog CMOS Integrated Circuits*, McGraw-Hill, Inc., 2001.

4.) R.J. Baker, H.W. Li and D.E. Boyce, *CMOS Circuit Design, Layout, and Simulation*, IEEE Press, 1998.

5.) D. Johns and K. Martin, *Analog Integrated Circuit Design*, John Wiley and Sons, Inc., 1997.

6.) K.R. Laker and W.M.C. Sansen, *Design of Analog Integrated Circuits and Systems*, McGraw-Hill, Inc., 1994.

7.) R.L. Geiger, P.E. Allen and N.R. Strader, *VLSI Techniques for Analog and Digital Circuits*, McGraw-Hill, Inc., 1990.

8.) A. Hastings, *The Art of Analog Layout* – 2nd Ed., Prentice-Hall, Inc., 2005.

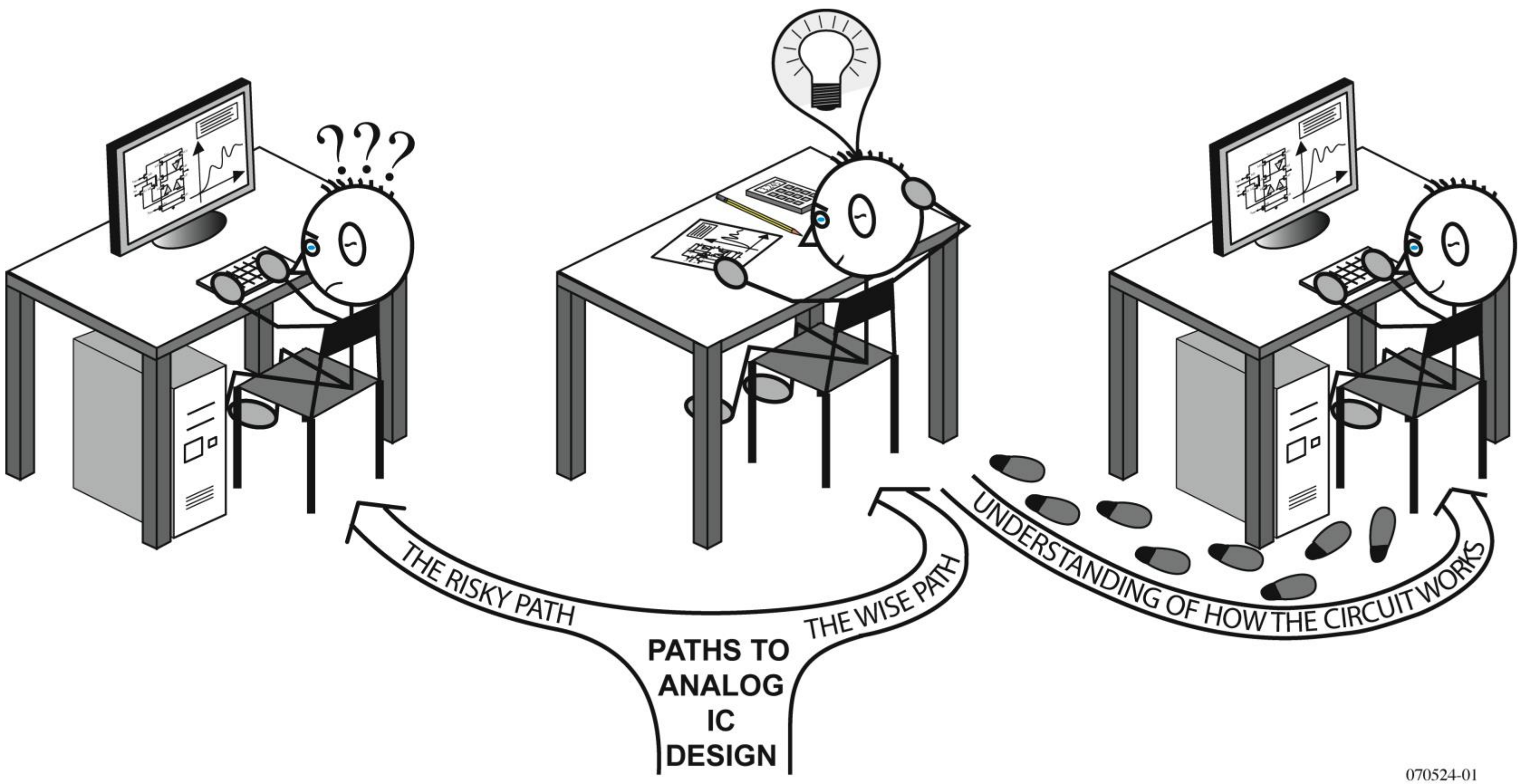
9.) J. Williams, Ed., *Analog Circuit Design - Art, Science, and Personalities*, Butterworth-Heinemann, 1991.

10.) R.A. Pease, *Troubleshooting Analog Circuits*, Butterworth-Heinemann, 1991.

Course Philosophy

This course emphasizes *understanding* of analog integrated circuit design.

Although simulators are very powerful, the designer must understand the circuit before using the computer to simulate a circuit.



WHAT IS ANALOG DESIGN?

The Analog IC Design Process

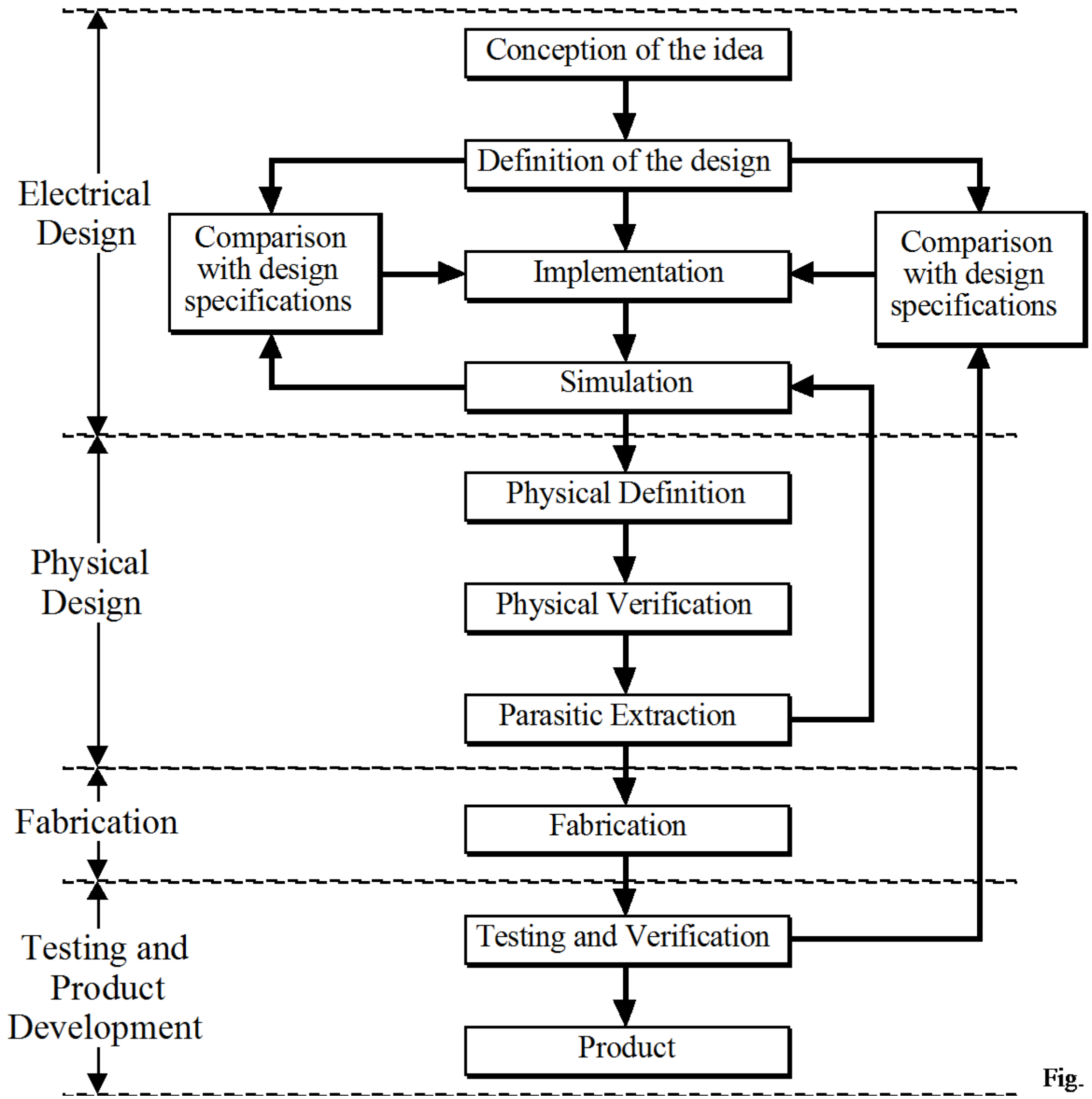


Fig. 1.1-2

What is Electrical Design?

Electrical design is the process of going from the specifications to a circuit solution. The inputs and outputs of electrical design are:

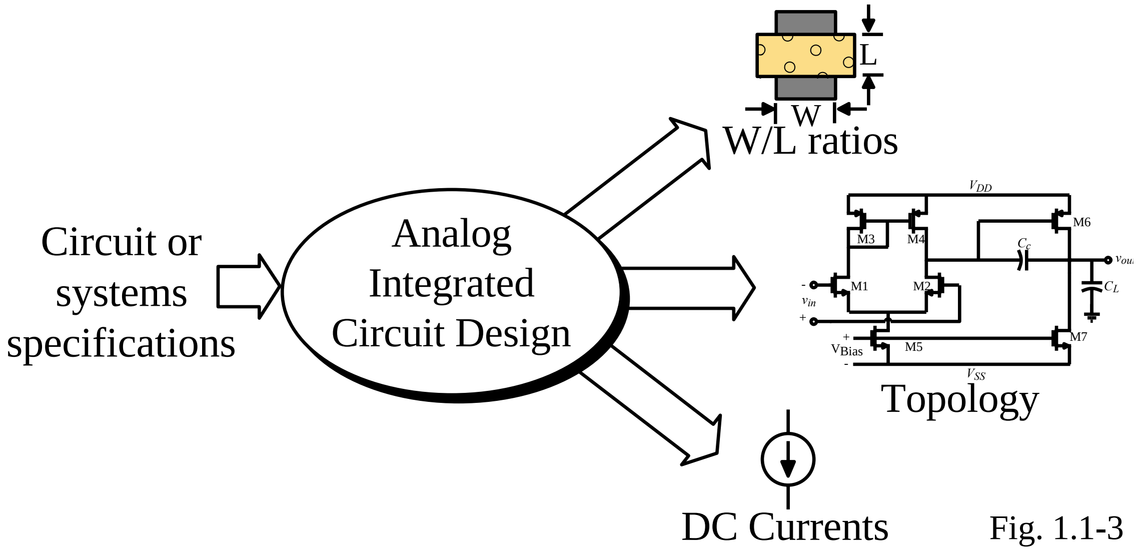


Fig. 1.1-3

The electrical design requires active and passive device electrical models for

- Creating the design
- Verifying the design
- Determining the robustness of the design

Steps in Electrical Design

1.) Selection of a solution

- Examine previous designs
- Select a solution that is simple

2.) Investigate the solution

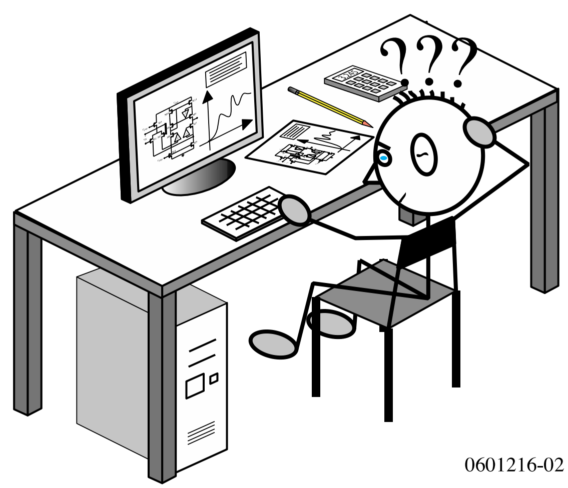
- Analyze the performance (without a computer)
- Determine the strengths and weaknesses of the solution

3.) Modification of the solution

- Use the key principles, concepts and techniques to implement
- Evaluate the modifications through analysis (still no computers)

4.) Verification of the solution

- Use a simulator with precise models and verify the solution
- Large disagreements with the hand analysis and computer verification should be carefully examined.



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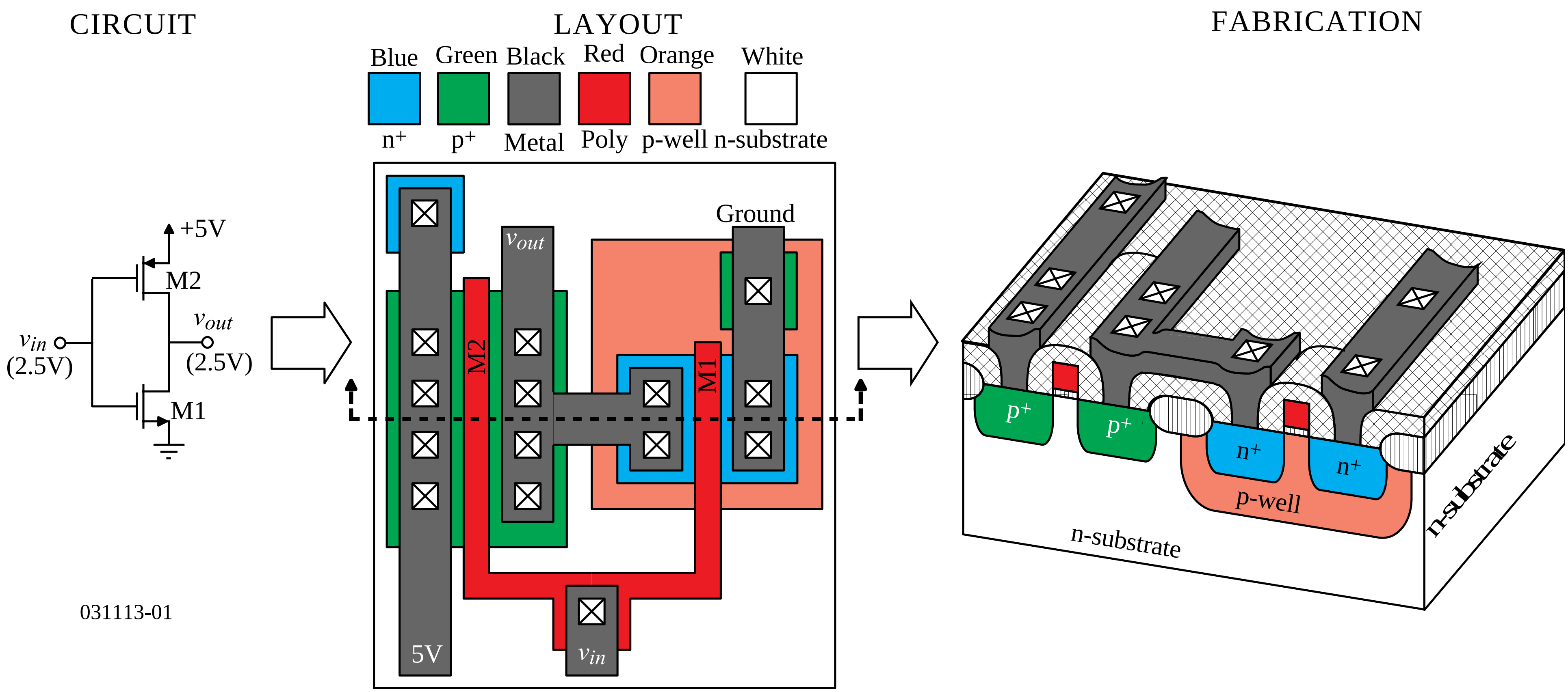
What is Physical Design?

Physical design is the process of representing the electrical design in a layout consisting of many distinct geometrical rectangles at various levels. The layout is then used to create the actual, three-dimensional integrated circuit through a process called *fabrication*.



What is the Layout Process?

1.) Inputs are the W/L values and the schematic (generally from schematic entry used for simulation).

2.) A CAD tool is used to enter the various geometries. The designer must enter the location, shape, and level of the particular geometry.

3.) During the layout, the designer must obey a set of rules called *design rules*. These rules are for the purpose of ensuring the robustness and reliability of the technology.

4.) Once the layout is complete, then a process called *layout versus schematic* (LVS) is applied to determine if the physical layout represents the electrical schematic.

5.) The next step is now that the physical dimensions of the design are known, the parasitics can be extracted. These parasitics primarily include:

a.) Capacitance from a conductor to ground

b.) Capacitance between conductors

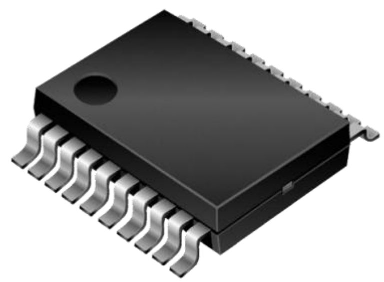
c.) Bulk resistance

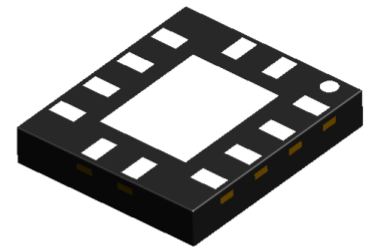
6.) The extracted parasitics are entered into the simulated database and the design is re-simulated to insure that the parasitics will not cause the design to fail.

Packaging†

Packaging of the integrated circuit is an important part of the physical design process.

The function of packaging is:





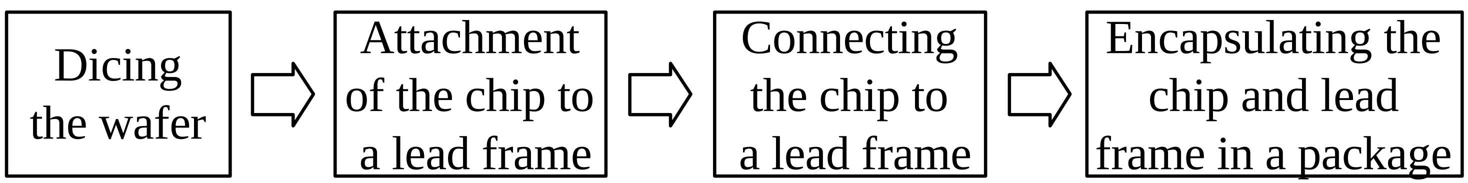
1.) Protect the integrated circuit

2.) Power the integrated circuit

3.) Cool the integrated circuit

4.) Provide the electrical and mechanical connection between the integrated circuit and the outside world.

Packaging steps:



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Other considerations of packaging:

- Speed
- Parasitics (capacitive and inductive)

† Rao Tummala, "Fundamentals of Microsystems Packaging," McGraw-Hill, NY, 2001.

What is Test Design?

Test design is the process of coordinating, planning and implementing the measurement of the analog integrated circuit performance.

Objective: To compare the experimental performance with the specifications and/or simulation results.

Types of tests:

- Functional – verification of the nominal specifications
- Parametric – verification of the characteristics to within a specified tolerance
- Static – verification of the static (AC and DC) characteristics of a circuit or system
- Dynamic – verification of the dynamic (transient) characteristics of a circuit or system

Additional Considerations:

Should the testing be done at the wafer level or package level?

How do you remove the influence (de-embed) of the measurement system from the measurement?

ANALOG INTEGRATED CIRCUIT DESIGN SKILLSET

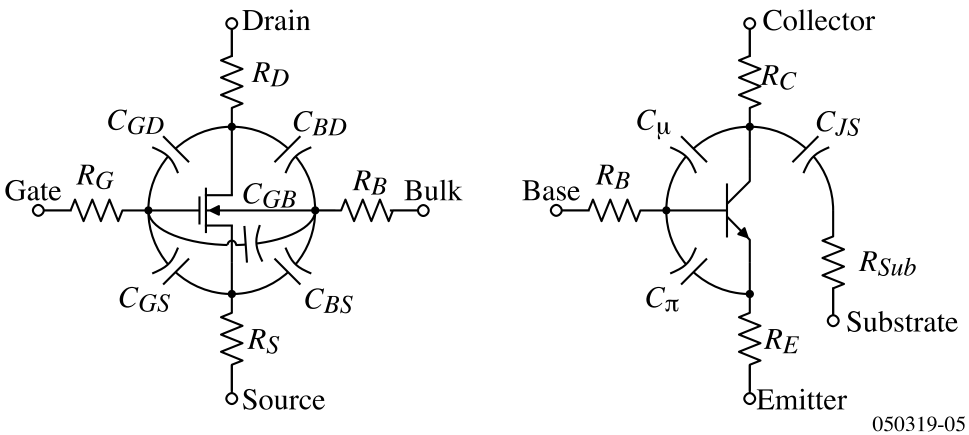
Characteristics of Analog Integrated Circuit Design

- Done at the circuits level
- Complexity is high
- Continues to provide challenges as technology evolves
- Demands a strong understanding of the principles, concepts and techniques
- Good designers generally have a good physics background
- Must be able to make appropriate simplifications and assumptions
- Requires a good grasp of both modeling and technology
- Have a wide range of skills - breadth (analog only is rare)
- Be able to learn from failure
- Be able to use simulation correctly

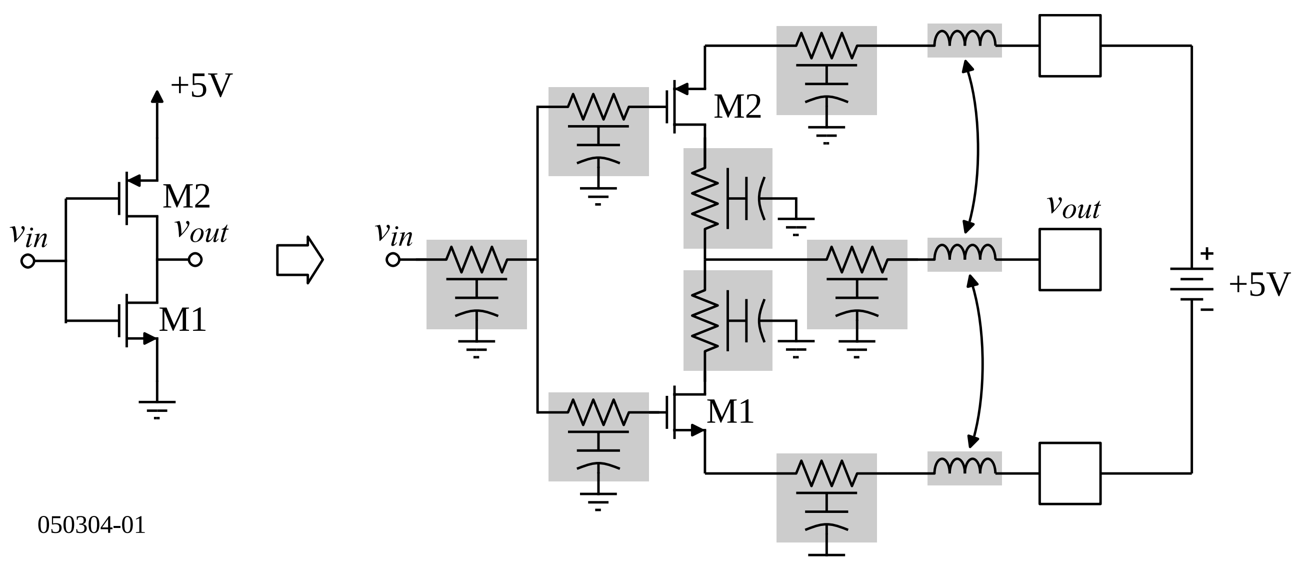
Understanding Technology

Understanding technology helps the analog IC designer to know the limits of the technology and the influence of the technology on the design.

Device Parasitics:



Connection Parasitics:

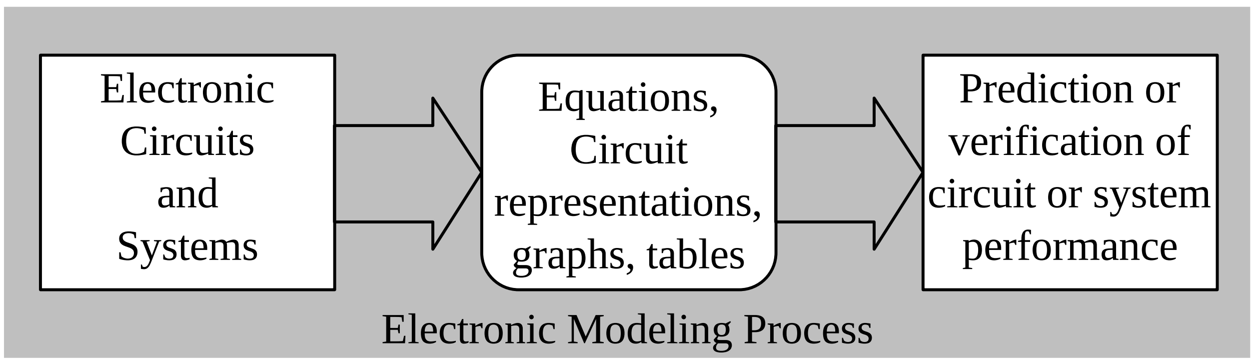


Understanding Modeling

Modeling:

Modeling is the process by which the electrical properties of an electronic circuit or system are represented by means of mathematical equations, circuit representations, graphs or tables.

Models permit the predicting or verification of the performance of an electronic circuit or system.



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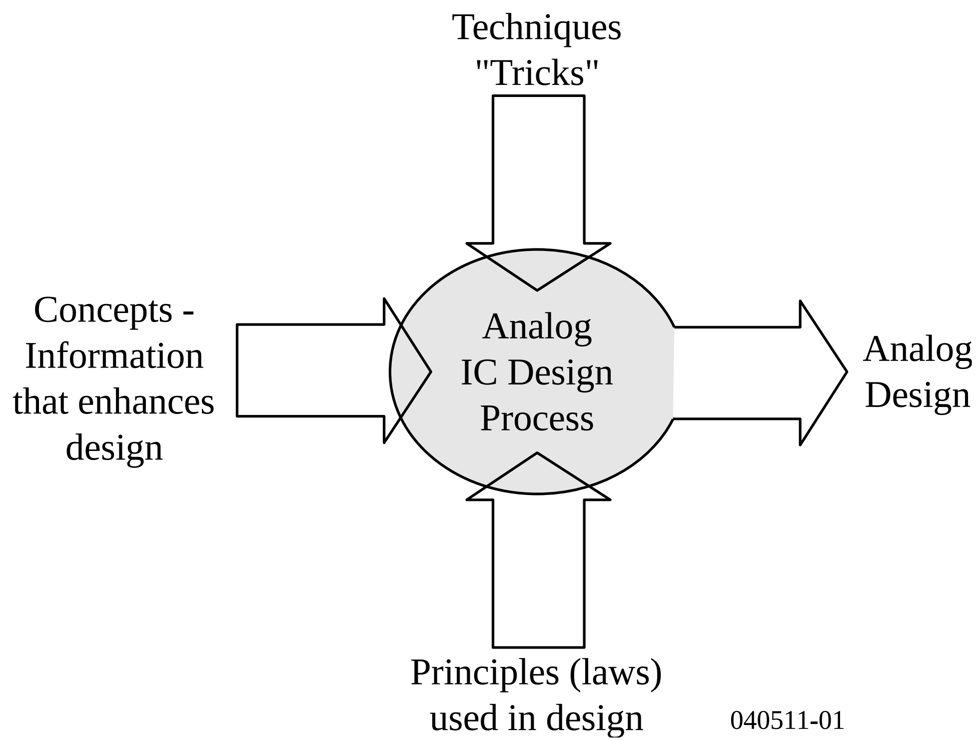
Examples:

Ohm's law, the large signal model of a MOSFET, the I-V curves of a diode, etc.

Goal:

Models that are simple and allow the designer to understand the circuit performance.

Key Principles, Concepts and Techniques of Analog IC Design



- Principles mean *fundamental laws* that are precise and never change.

  (Webster – A comprehensive and fundamental law, doctrine, or assumption. The laws or facts of nature underlying the working of an artificial device.)

- Concepts will include *relationships*, "soft-laws" (ones that are generally true), analytical tools, things worth remembering.

  (Webster – An abstract idea generalized from particular instances.)

- Techniques will include the assumptions, "tricks", tools, *methods* that one uses to simplify and understand.

  (Webster – The manner in which technical details are treated, a method of accomplishing a desired aim or goal.)

Complexity in Analog Design

Analog design is normally done in a non-hierarchical manner and makes little use of repeated blocks. As a consequence, analog design can become quite complex and challenging.

How do you handle the complexity?

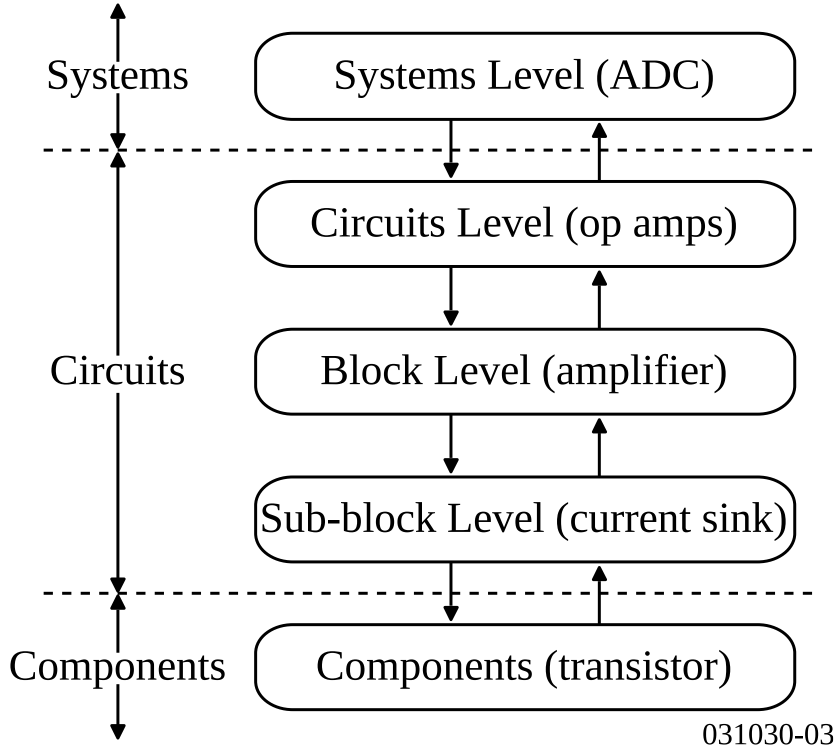
1.) Use as much hierarchy as possible.

2.) Use appropriate organization techniques.

3.) Document the design in an efficient manner.

4.) Make use of assumptions and simplifications.

5.) Use simulators appropriately.



Assumptions

Assumptions:

An assumption is taking something to be true without formal proof. Assumptions in analog circuit design are used for simplifying the analysis or design. The goal of an assumption is to separate the essential information from the nonessential information of a problem.

The elements of an assumption are:

1.) Formulating the assumption to simplify the problem without eliminating the essential information.

2.) Application of the assumption to get a solution or result.

3.) Verification that the assumption was in fact appropriate.

Examples:

Neglecting a large resistance in parallel with a small resistance

Miller effect to find a dominant pole

Finding the roots of a second-order polynomial assuming the roots are real and separated

WHERE IS ANALOG IC DESIGN TODAY?

Analog IC Design has Reached Maturity

There are established fields of application:

- Digital-analog and analog-digital conversion
- Disk drive controllers
- Modems - filters
- Bandgap reference
- Analog phase lock loops
- DC-DC conversion
- Buffers
- Codecs
- Etc.

Existing philosophy regarding analog circuits:

"If it can be done economically by digital, don't use analog."

Consequently:

Analog finds applications where speed, area, or power have advantages over a digital approach.

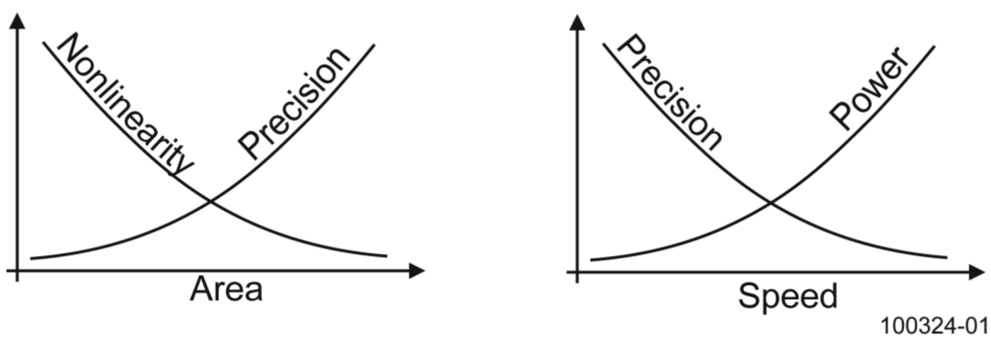
Analog IC Design Challenges

Technology:

- Digital circuits have scaled well with technology
- Analog does not benefit as much from smaller features
  - Speed increases
  - Gain decreases
  - Matching decreases
  - Nonlinearity increases
  - New issues appear such as gate current leakage

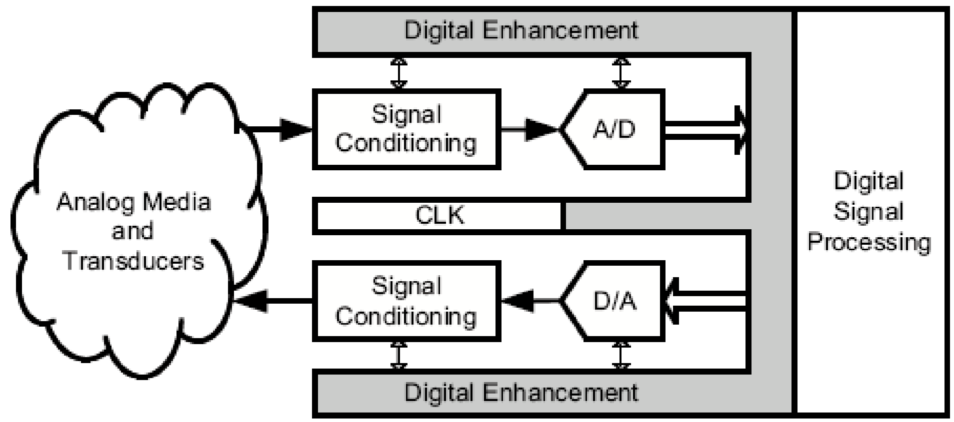
Analog Circuit Challenges:

- Trade offs are necessary between linearity, speed, precision and power



- As analog is combined with more digital, substrate interference will become worse

Digitally Assisted Analog Circuits



Use digital circuits which work better at scaled technologies to improve analog circuits that do not necessarily improve with technology scaling.

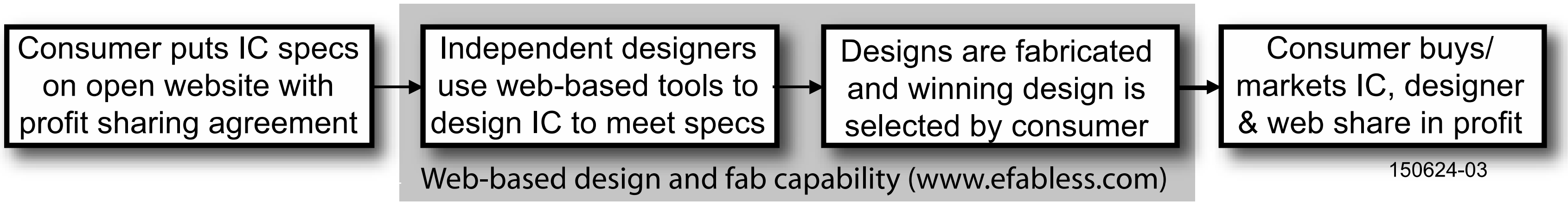
Principles and Techniques:

- Open-loop vs. closed loop
  - Open loop is less accurate but smaller $\Rightarrow$ □Faster, less power
  - Closed-loop is more accurate but larger $\Rightarrow$ □Slower, more power
- Averaging
  - Increase of accuracy $\Rightarrow$ □Smaller devices, more speed
- Calibration
  - Accuracy increases $\Rightarrow$ □Increased resolution with same area
- Dynamic Element Matching
  - Enhancement of component precision
- Doubly correlated sampling
  - Reduction of dc influences (noise, offset) $\Rightarrow$ Smaller devices, more speed
- Etc.

A New Paradigm for IC Design?

- Today's Paradigm
  - $ invested up front
  - No guarantee that product will be profitable
  - Requires a lot of overhead, support, and time

- New Paradigm (shaped by the internet)



  - No $ invested until the product is sold
  - The need for an IC is generated by potential consumer
  - Opens the design space to a wide range of "designers"
  - Massive markets not needed to make a product and profit
  - Minimizes the time and overhead required to develop a product
  - Design equivalent of crowd funding ➞ "crowd designing"

NOTATION, TERMINOLOGY AND SYMBOLOGY

Definition of Symbols for Various Signals

Signal Definition	Quantity	Subscript	Example
Total instantaneous value of the signal	Lowercase	Uppercase	q_A
DC value of the signal	Uppercase	Uppercase	Q_A
AC value of the signal	Lowercase	Lowercase	q_a
Complex variable, phasor, or rms value of the signal	Uppercase	Lowercase	Q_a

Example:

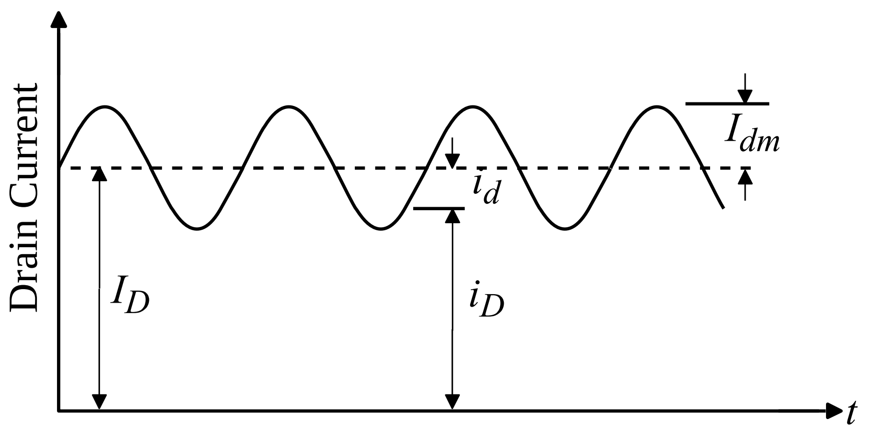
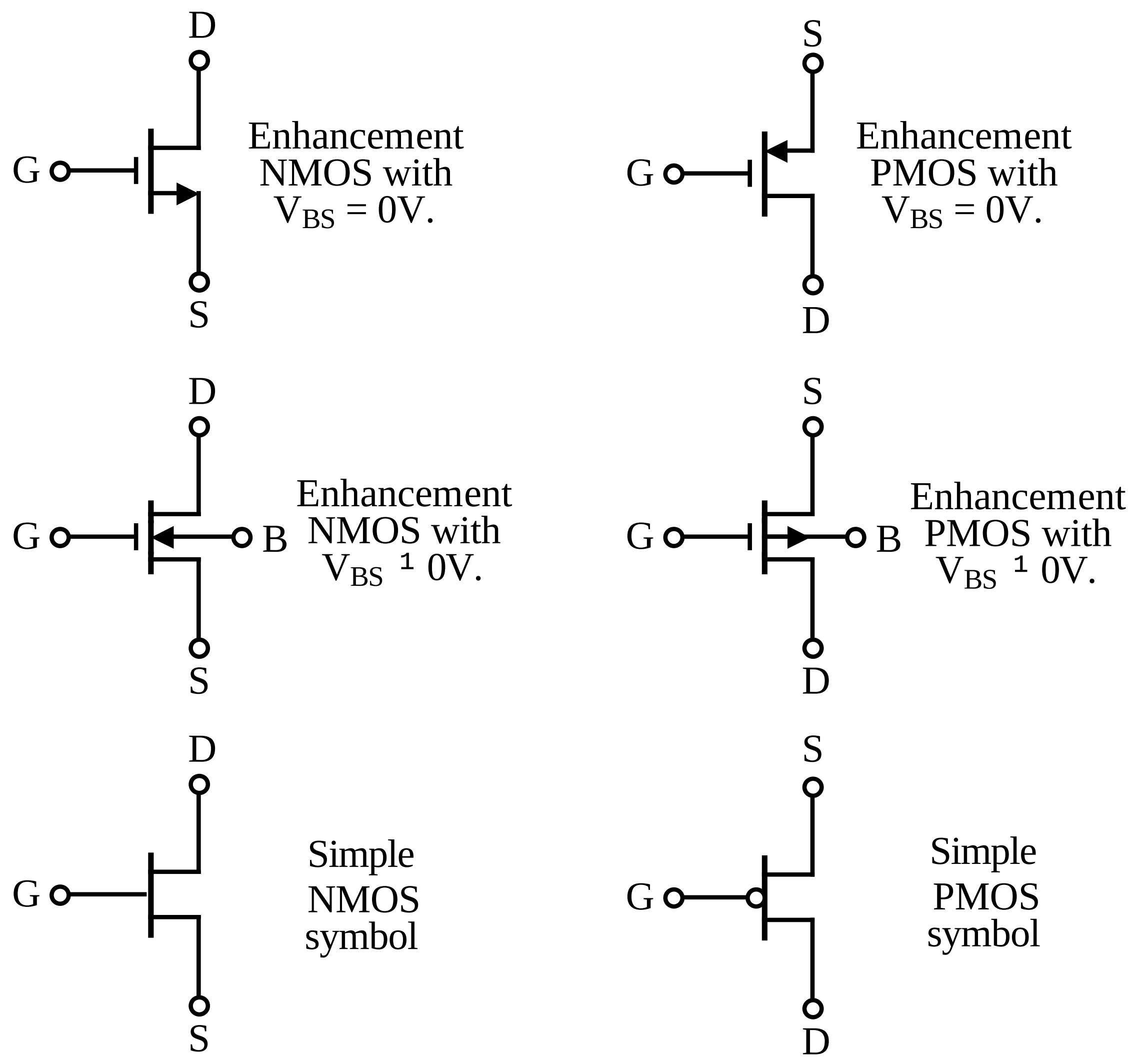
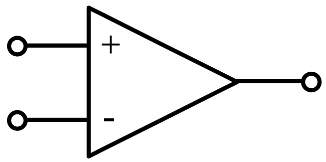


Fig. 1.4-1

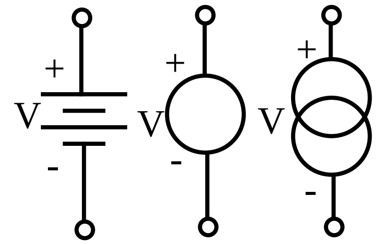
MOS Transistor Symbols



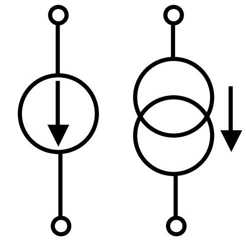
Other Schematic Symbols



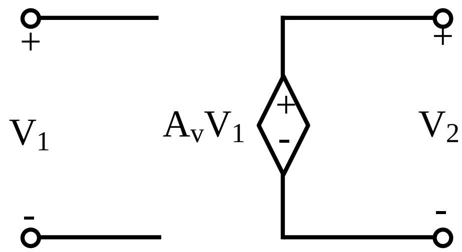
Differential amplifier,
op amp, or comparator



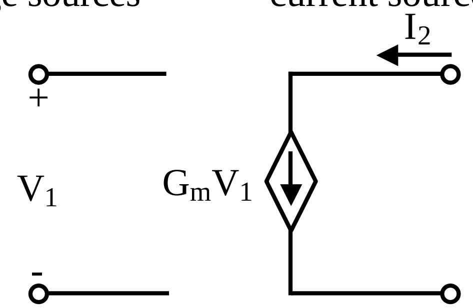
Independent
voltage sources



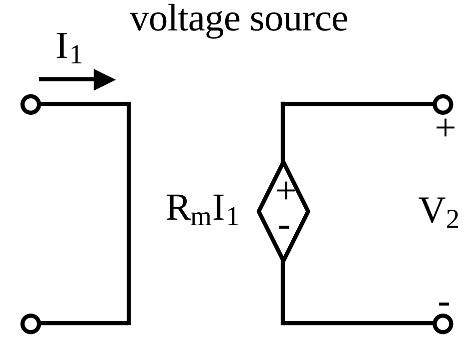
Independent
current source



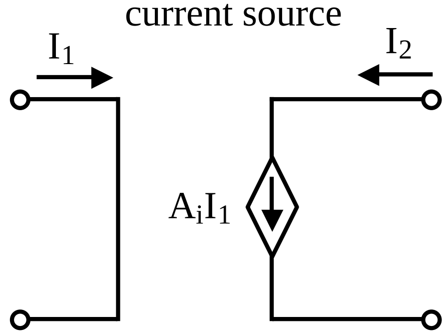
Voltage-controlled,
voltage source



Voltage-controlled,
current source



Current-controlled,
voltage source



Current-controlled,
current source

Three-Terminal Notation

***Q**ABC*

A = Terminal with the larger magnitude of potential

B = Terminal with the smaller magnitude of potential

C = Condition of the remaining terminal with respect to terminal B

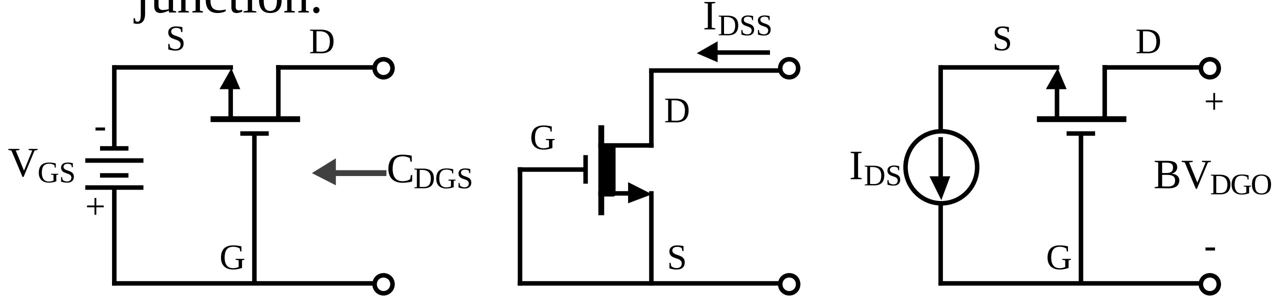
C = *0* ⇒ There is an infinite resistance between terminal B and the 3rd terminal

C = *S* ⇒ There is a zero resistance between terminal B and the 3rd terminal

C = *R* ⇒ There is a finite resistance between terminal B and the 3rd terminal

C = *X* ⇒ There is a voltage source in series with a resistor between terminal B and the 3rd terminal in such a manner as to reverse bias a PN junction.

Examples



(a.) (b.) (c.)

(a.) Capacitance from drain to gate with the source shorted to the gate.

(b.) Drain-source current when gate is shorted to source (depletion device)

(c.) Breakdown voltage from drain to gate with the source is open- circuited to the gate.

SUMMARY

- Successful analog IC design proceeds with understanding the circuit before simulation.
- Analog IC design consists of three major steps:

  1.) Electrical design ⇒ Topology, W/L values, component values and dc currents

  2.) Physical design (Layout)

  3.) Test design (Testing)
- Analog designers must be flexible and have a skill set that allows one to simplify and understand a complex problem
- Analog IC design has reached maturity and is here to stay.
- The appropriate philosophy is "If it can be done economically by digital, don't use analog".
- As a result of the above, analog finds applications where speed, area, or power result in advantages over a digital approach.
- Deep-submicron technologies will offer exciting challenges to the creativity of the analog designer.
- Paradigm for IC design might be changing which would influence analog IC design.

