THE PRACTICE OF ANALOG IC DESIGN

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INTRODUCTION

Practice

(Webster) – The condition of being proficient through systematic exercise. The continuous exercise of a profession by a professional.

Objective

Help understand what is analog IC design and how to do it successfully and productively.

Focus Questions

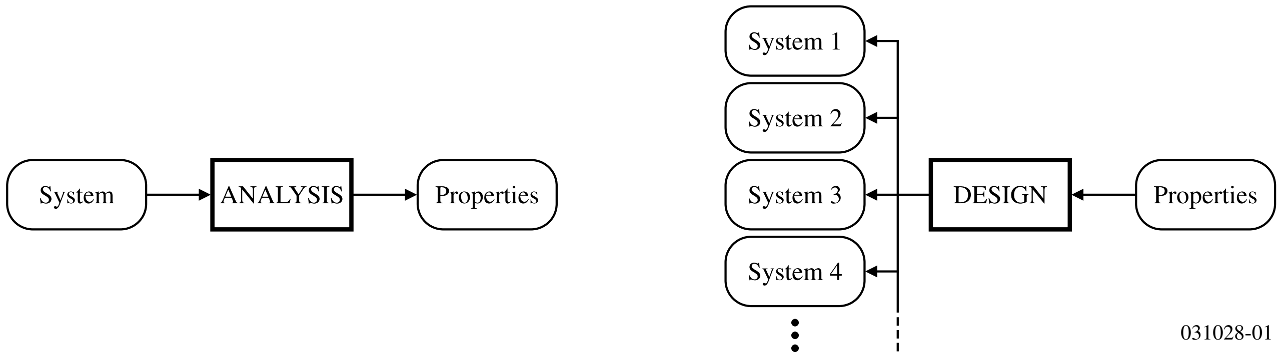
- What is analog circuit design?
- What is the analog integrated circuit design process?
- What are the key principles, concepts and techniques for analog IC design?
- How can the analog IC designer enhance creativity and solve new problems in today's industrial environment?

WHAT IS ANALOG DESIGN?

Definition

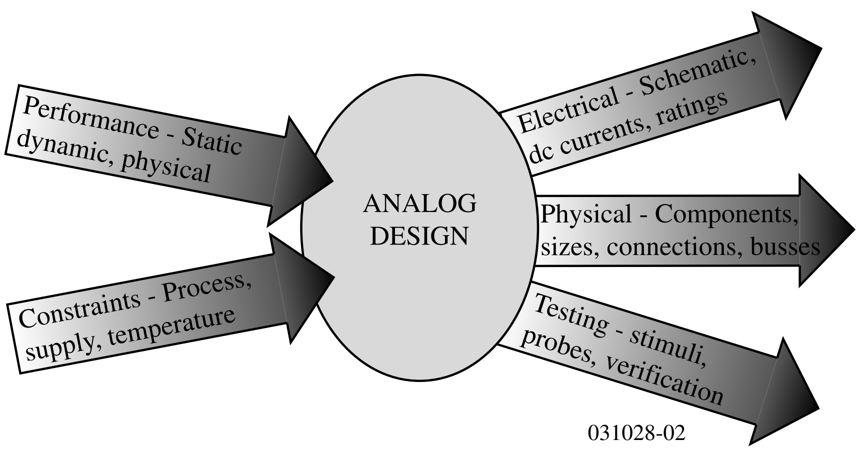
Design – To create or execute in an artistic or highly skilled manner. The invention and disposition of the forms, parts, or details of something according to a plan. (Webster)

Analysis versus synthesis (design)



- Analysis: Given a system, find its properties. The solution is unique.
- Design: Given a set of properties, find a system possessing them. The solution is rarely unique.

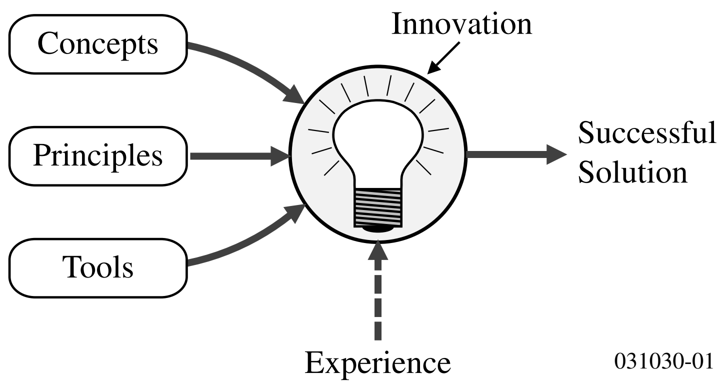
What are the Inputs and Outputs of Design?



- Inputs are the properties or specifications.
  - Performance – static, dynamic, physical
  - Constraints – process, supply voltages, temperature
- Outputs is the system or solution
  - Electrical – schematic, dc currents, ratings
  - Physical – components, sizes, connections, busses
  - Testing – stimuli, probes, loading, verification procedures

Innovation and Invention with respect to Design

What is innovation?



Innovation is the ability to apply the concepts, principles and tools pertinent to analog design and create a unique solution.

Some of the characteristics of innovation:

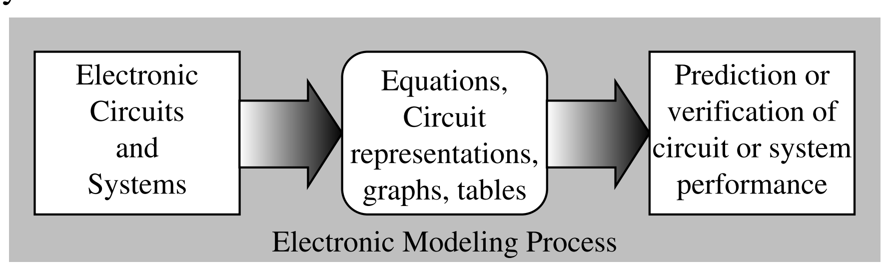
- Understand the principles, concepts, and tools (methods)
- Organized thinking (able to grasp cause and effect)
- Experience and intuition

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.

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

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?

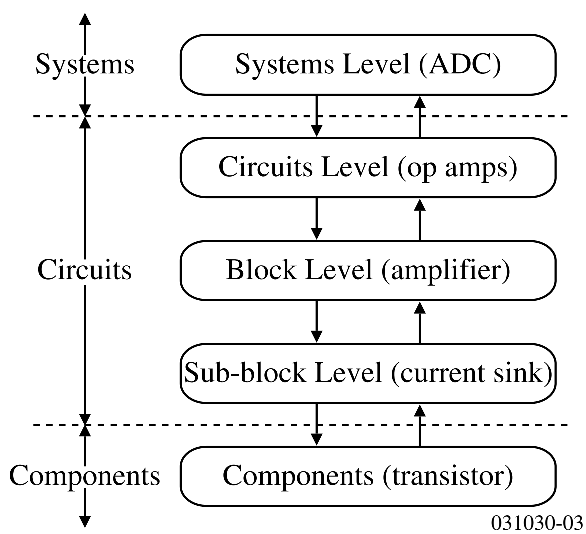
1.) Use as much hierarchy as possible.

2.) Use appropriate organization techniques.

3.) Document the design in an efficient manner.

4.) Make use of assumptions and simplifications.

5.) Use simulators appropriately.



Analog design is sometimes called “organized chaos”.

Characteristics of Analog 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

WHAT IS THE ANALOG IC DESIGN PROCESS?

What is the Difference between Discrete and Integrated Analog IC Design?

The primary difference is in the physical aspects of the components:

Design Characteristic	Discrete Analog Design	Integrated Analog Design
Tolerance of Components	Can be whatever the designer wants	Very poor absolute tolerance better relative tolerance
Range of values	Unlimited	Limited
Design of the Components	Little influence over the design	Total influence over the design
Impact of the Components	Very little, can be minimized	Strong influence, cannot be minimized
Dependence of the electrical and physical design	Independent	Dependent
Testing	Relatively easy to test any aspect of the circuit. Can change components.	Testing must be incorporated into the entire design phase or will not be possible
Technology Dependence	Very little	Strongly dependent

Demands on Analog IC Designer

- The design process must be highly structured and organized (and at the same time allow for flexibility and creativity)
- The design complexity increases quickly not only because the number of components but because of the interaction between the electrical, physical and testing aspects of the design.

  Consequently,

  - The designer must make correct use of the appropriate CAD tools
  - The designer must be able to work effectively as a team member
- The designer must understand the technology
  - What are the limitations and influence of the technology on the design?
  - How can the technology be used to overcome design limitations?
  - How does technology influence the reliability of the design?
- The designer must understand the application of the design
  - What are the implications of the specifications?
  - What aspects of the systems influence the circuit performance?
  - Where are the performance limiting aspects of the system or circuit?
- Analog integrated circuit design is an ever-changing profession – a dynamic profession

The Analog IC Design Process

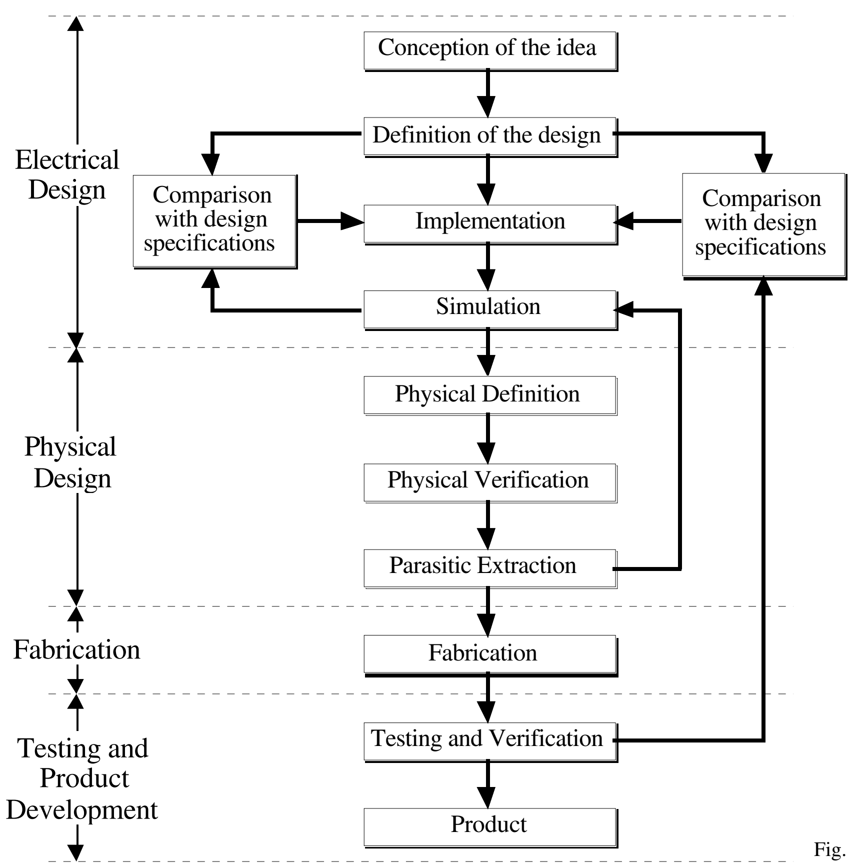
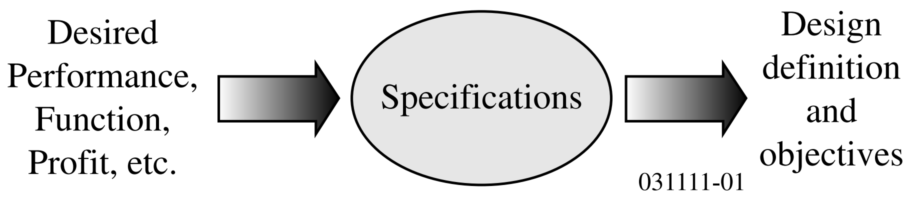


Fig. 1.1-2

What are Specifications?

A specification is a detailed and exact statement for the design of a circuit or system. It generally describes the desired performance and the conditions under which that performance should be achieved. *The specifications define the design.*



Goals of a specification:

The specification should define the desired final result but not necessarily every step in reaching that result.

The specification must be verifiable (it must be able to be confirmed)

The specification must include all necessary information (i.e. load conditions, etc.)

Various aspects of specifications:

- Business (political)
- Technical
- Conflicts

Business Aspects of Specifications

Negotiation – rarely are specifications defined without mutual agreement between the parties.

Hard vs. soft specifications – the designer must know what specifications cannot be changed and which are more flexible.

Fact vs. fiction – Does the specification make sense? The designer must be able to evaluate the validity of the specification.

Legal aspects – the specification is an agreement and may be informal or formal

If the specification is formal, the designer should thoroughly examine the specifications before accepting the responsibility to create a design to achieve the specifications.

Will the design infringe on one or more patents?

Technical Aspects of Specifications

Can be in the form of:

1.) Performance objectives
2.) Environmental constraints
3.) Technological constraints

Can the spec be exceeded?

It is very difficult to exactly meet a performance specification so does the specification have a threshold that can be exceeded?

Will the design be testable?

Will the design be compatible with the technology?

Will the design be robust and reliable?

Make sure all technical aspects of the specifications are clearly understood.

Dealing with Conflicting or Difficult Specifications:

Some possible approaches to conflicting or difficult specifications-

1.) Ignore – the result is that the circuit will probably not be successful
2.) Negotiate a change in the specification
3.) Solve the difficulty through design creativity ("Start designing and quit whining." – response to multi-chip proponents on a 1998 ISSCC Panel on Single-Chip versus Multi-Chip solutions for RF ICs.)

Pick your battles wisely-

Keep the global objectives in mind –

Be sure to win the "war" even at the cost of a few "battles".

Tradeoffs and priorities

Select the best possible compromise with respect to the global objective

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:

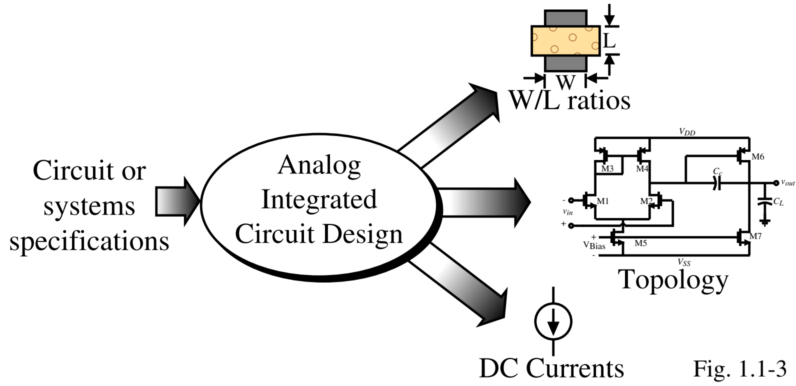


Fig. 1.1-3

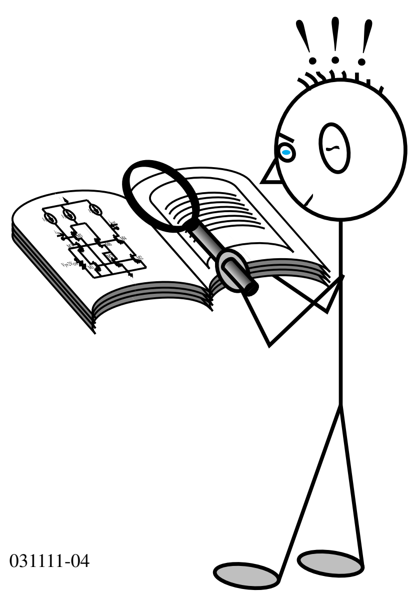
The electrical design requires active and passive device electrical models for

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

Steps in Electrical Design

1.) Selection of a solution

- Examine previous designs
  - Literature
  - Patents
  - Textbook
  - Web
  - Your previous experience (if you are new in the field this is a challenge)
  - Experienced colleagues
- Select a solution that:
  - Is simple
  - You understand – don't be afraid to use "recipes"
  - Has the potential to meet the specifications



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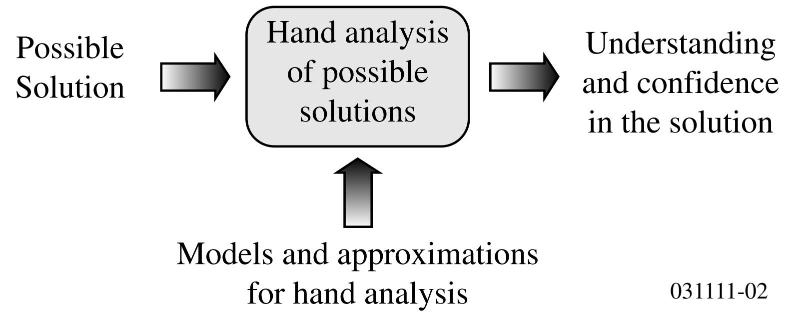
Steps in Electrical Design - Continued

2.) Investigation of a solution

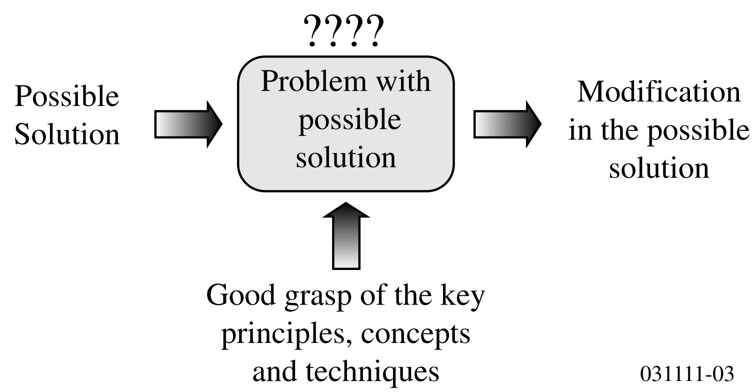
- Analyze, analyze, analyze
- Determine the ability of the solution to satisfy most or all of the specifications
- Observe the weaknesses and strengths of the solution
- "Get a feeling" for the circuit operation



Steps in Electrical Design - Continued

3.) Modification of a solution

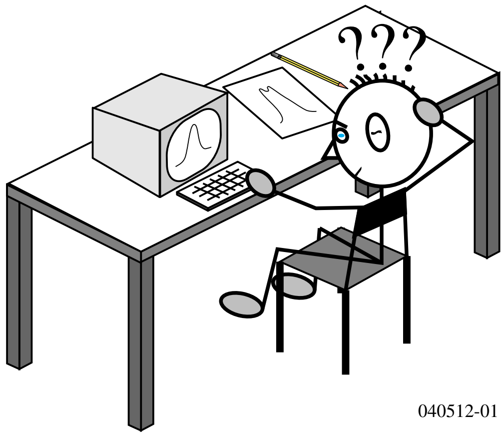
- The previous step should identify the weaknesses or inability to satisfy the specifications
- Look for modifications in the design to improve its performance (the key principles, concepts and techniques in this study will be a great help in this step)
- Evaluate the modifications through analysis
- Most of the analysis up to this point in the design *has not used a computer or a model that is precise*



Steps in Electrical Design - Continued

4.) Verification of a solution

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



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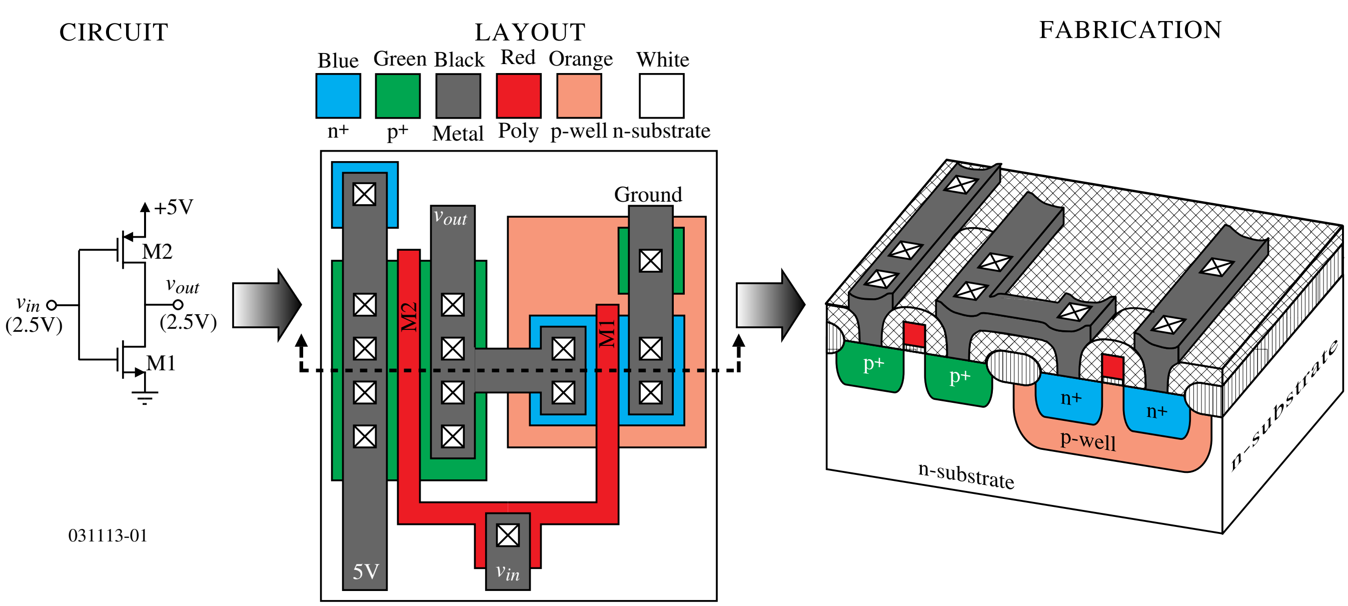
- Use models that capture the technology variations to make sure the design will work for the given technology (if this information is not available, run the circuit over a wide temperature range to get similar results)

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*.



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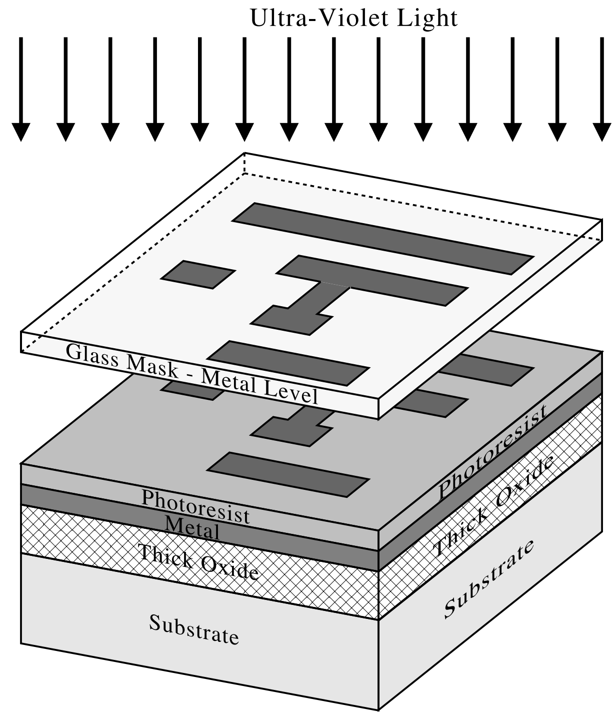
What is the Purpose of the Layout?

The layout is used to create the masks that enable the fabrication of the chip.

Metal level mask example:



What is the Layout Process?

1.) The 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.

Design Rules

What are the failure mechanisms in the technology that design rules attempt to prevent[†]?

Failure Mechanism	Effects	Preventative Measures
Electrostatic Discharge	Gate oxide ruptures or is degraded	Apply ESD protection structures which limit the voltage at the pads
Electromigration	Open or short circuits after long-term operation, usually at high temperature	Make metal widths wider, use copper or saliciding
Antenna Effect	Small gate oxides connected to large polysilicon areas can suffer damage due to electric fields generated during processing	Reduce the polysilicon area connected to the small gate oxides or put a metal jumper in series with it.
Metal Fracturing	Metal deposited on sharp steps can to thin to pass the required current	Avoid sharp steps – replace by several smaller steps

† Alan Hastings, "The Art of Analog Layout", Chap. 4, Prentice-Hall, New Jersey, 2001

Packaging[†]

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

The function of packaging is:

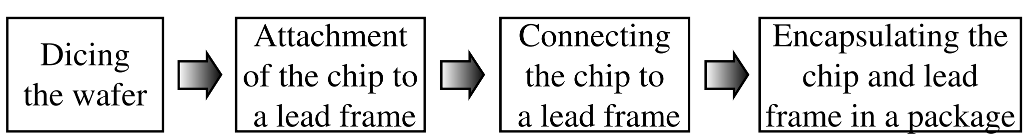
1.) Protect the integrated circuit

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?

WHAT ARE THE KEY PRINCIPLES, CONCEPTS AND TECHNIQUES OF ANALOG IC DESIGN?

Is Analog Design an Art or Science?

"Maybe the problem is that analog design is an art and it is difficult to teach an art."

A simplistic definition of Art and Science:

It is art if you *can't* explain how it works.

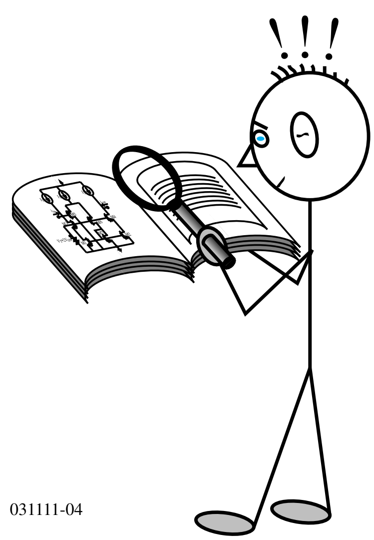
It is science if you *can* explain how it works.

A corollary to the above definition:

Art is when someone else can explain it but you can't.

Science is when you can explain it but someone else can't.

Analog design should be more of a science than an art.



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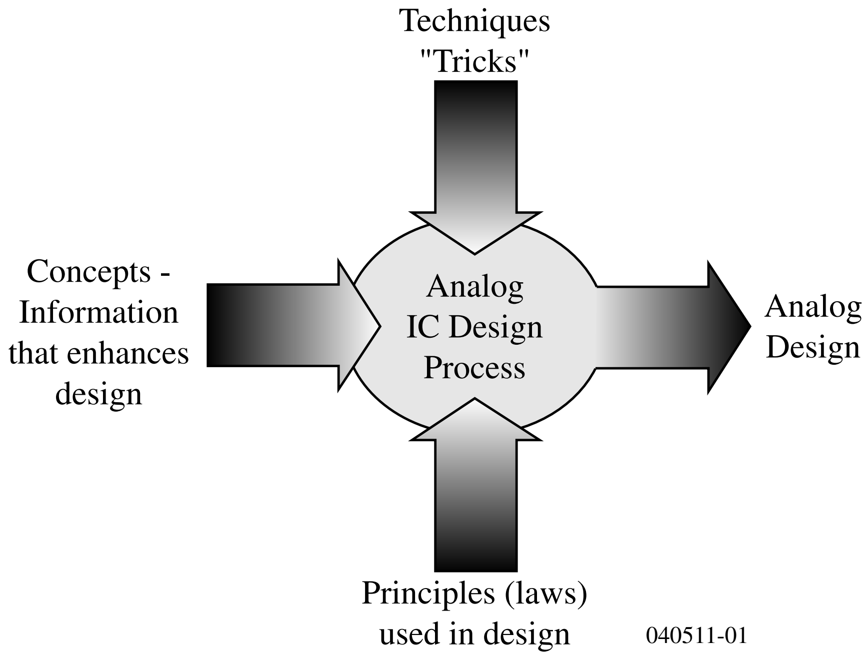
Key Principles, Concepts and Techniques

Illustration:



Key Principles of Analog IC Design

Principles will be used here to 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.)

Examples:

Circuit laws:

- KVL, KCL, Thevinen-Norton, Ohms, superposition, linearity, time invariance, substitution, bisection, Millers theorem, etc.
- $i = C\frac{dv}{dt}$, $v = L\frac{di}{dt}$

Stability – Bode criterion, root-locus criterion

Fourier analysis

Nyquist relationship between the data frequency and clock frequency

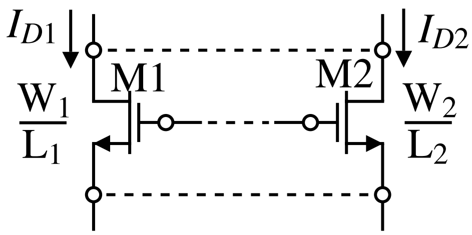
Doubly correlated sampling

z-domain relationships

Laplace transforms

Example of a Key Principle

"If the gate, source and drain terminals of two matched transistors are at the same potential, their currents are related through their W/L ratios."



(Unfortunately, this principle must be coupled with matching principles associated with the physical layout of the two transistors as well.)

Key Concepts of Analog IC Design

Concepts will include *relationships*, "soft-laws" (ones that are generally true), analytical tools, things worth remembering. (Webster – An abstract idea generalized from particular instances.)

Examples:

- Models – Large and small signal, behavioral modeling
- Poles and zeros – how to find them by inspection, root locus
- Output and input resistance of cascode circuits
- Dynamic range
- Feedback-types, effect on performance, positive and negative, feedback loops
- Feedforward
- Component accuracy is inversely proportional to size
- Accuracy enhancement
  - Increasing area
  - Averaging/interpolation
  - Dynamic element matching
- Bode plots, frequency response

Key Concepts of Analog IC Design - Continued

Physical matching of components
- Replication principle
- Minimization of the periphery
- Statistical "scattering" with increased unit cells
- Definition of the area between two plates by making one smaller than the other
- Photolithographic invariant layout

Component matching:
1.) Use identical structures (with the same area/periphery ratio)
2.) Replicate identical structures (average → ideal)
3.) Increase area
4.) Minimize edge and maximize area (geometry)
5.) Use the smaller of two horizontal plates to define the common area.

Identification of element parasitics with the geometrical properties of the element

Example of a Key Concept

Feedback (an excellent concept but generally not good for analysis):

Feedback Type	Input/Output Resistance w/o Fb.	Input/Output Resistance with Fb.
Negative-Series	R	R(1 + Loop Gain)
Negative-Shunt	R	$\frac{R}{1 + \text{Loop Gain}}$
Positive-Series	R	R(1 - Loop Gain)
Positive-Shunt	R	$\frac{R}{1 - \text{Loop Gain}}$

Therefore, to decrease the output resistance of a MOSFET circuit below the value of $1/g_m$, one *must* use some form of negative-shunt feedback.

Key Techniques of Analog IC Design

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.)

Examples:

$V_{ab} = V_a - V_b$

$|p_1| < |p_2|$ for a system with 2 real roots

$x = A + Be^{-t/\tau}$ $\tau = RC$ (C = one eq. capacitance, R = Thevinen resistance seen from C)

$g_m \approx 10\, g_{mbs} \approx 100\, g_{ds}$

Debugging techniques

Effective transconductance of a transistor with source resistance

Zero TC MOSFET biasing

Use of ratios to minimize component variation

How to make assumptions

- Simplify without removing the essence of the problem
- Use the simplification to achieve the desired objective
- Check the assumption for validity

Use of a simulator to verify, explore, and/or optimize a circuit

Biasing techniques: V_{DD} -V_{TP} -2V_{ON}, V_{DD} -V_{TP} –V_{ON}, V_{TN} +2V_{ON}, and V_{TN} +V_{ON}

Illustration of a Key Technique

Worst case analysis:

Estimate the worst case error between the ratio of two variables, x_2 and x_1, if the relative accuracy, $\Delta x/x$, is known. Note: Ideally $x_2 = x_1$.

1.) Define $\Delta x = x_2 - x_1$ and $x = \dfrac{x_1 + x_2}{2}$.

2.) Solve for $x_2 = x + 0.5\Delta x$ and $x_1 = x - 0.5\Delta x$ from the definitions in 1.).

3.) Substitute these values of x_1 and x_2 into the ratio to get,

$$\frac{x_2}{x_1} = \frac{x + 0.5\Delta x}{x - 0.5\Delta x}$$

4.) Factor out x,

$$\frac{x_2}{x_1} = \frac{1 + \dfrac{0.5\Delta x}{x}}{1 - \dfrac{0.5\Delta x}{x}} \approx \left(1+\frac{0.5\Delta x}{x}\right)\left(1+\frac{0.5\Delta x}{x}\right)$$

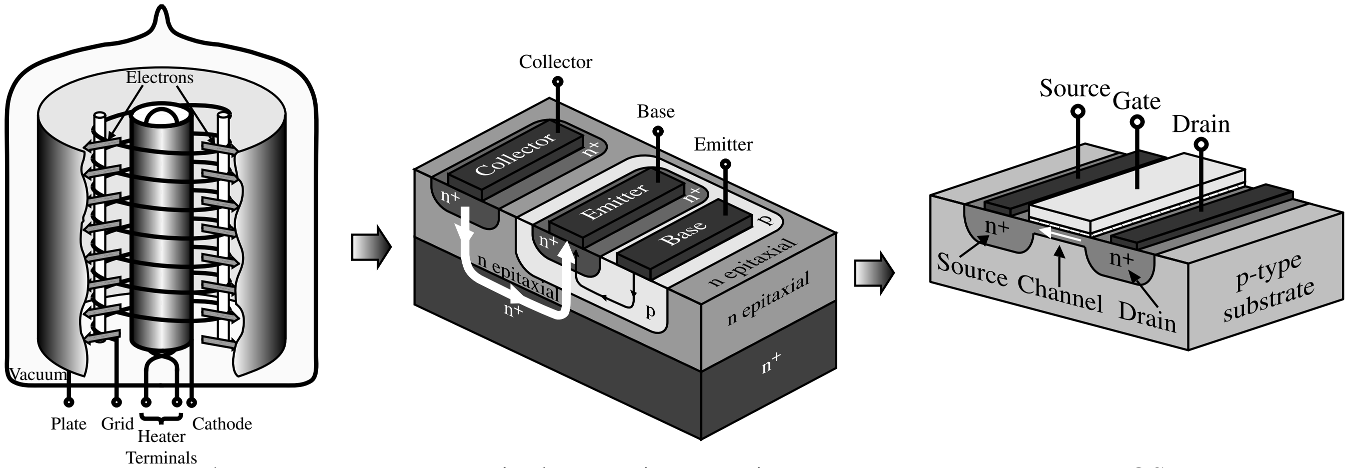
5.) Replace the denominator with the first two terms of a power series and ignore away higher order terms.

$$\frac{x_2}{x_1} = 1 + \frac{\Delta x}{x} + \left(\frac{\Delta x}{2x}\right)^2 \approx 1 + \frac{\Delta x}{x}$$

HOW CAN THE ANALOG IC DESIGNER ENHANCE CREATIVITY AND SOLVE NEW PROBLEMS IN TODAY'S INDUSTRIAL ENVIRONMENT?

Understand the Key Principles, Concepts and Techniques

These factors never change over time.



Vacuum Tube	Bipolar Junction Transistor	MOSFET
Field emission	Diffusion Current	Drift Current
1930's	1950's	1970's

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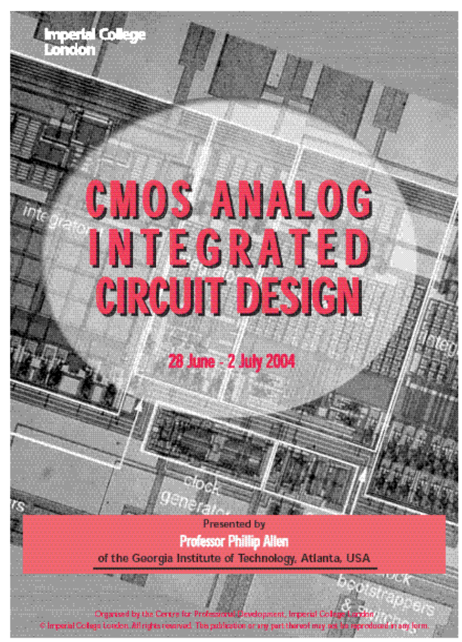
Large-signal and small-signal models are essentially identical for differing technologies.

Learn, Learn and Continue to Learn

- Take short courses
- Enroll in advanced degrees
- Read the pertinent journals (*IEEE Solid-State Circuits Journal*, *Analog Integrated Circuits and Signal Processing Journal*, *IEEE Trans. on Circuits and Systems*, etc.)
- Attend conferences (International Solid-State Circuits Conference – Feb.)
- Attend meetings such as this one



Learn From Mistakes

Failure should be considered as an opportunity to learn.

The desirable result from failure should be:

1.) A good understanding of what has failed and why.

2.) An opportunity to build your understanding and not repeat the failure.

3.) An opportunity to build character – "what happens to you is not nearly as important as how you respond to what happens to you".

What about failure in a pressure environment?

1.) The temptation is to find the quickest solution without ever understanding the problem. The following are bad ideas:

- Consult with the local "expert"
- Randomly try alternatives
- Avoid the problem altogether

2.) If this is the case, analyze the failure later (possibly on your own time because what you learn is part of your professional growth).

Troubleshooting†

What is it?

Troubleshooting is the process of identifying why a circuit does not work. In the process, it is most desirable to understand how to fix the problem.

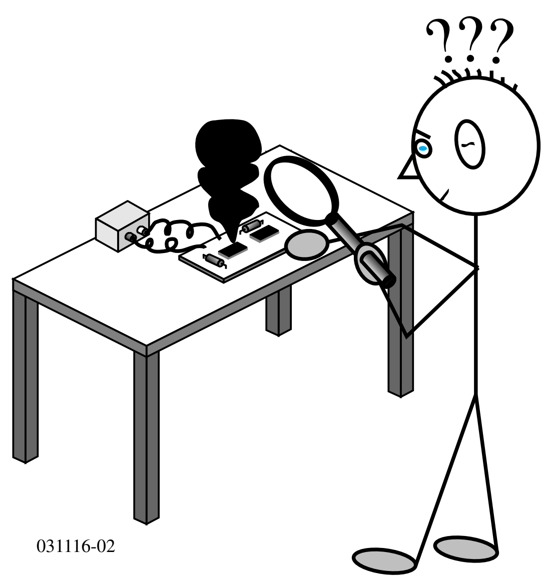
How is troubleshooting accomplished?

1.) Investigation – gathering facts about the problem

2.) Formulating what might be wrong based on the investigation (hypothesis)

3.) Testing the hypothesis to see if it is correct

In many respects, troubleshooting is very similar to the work of a detective.



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† Robert Pease, "Troubleshooting Analog Circuits," Butterworth Heinemann, Woburn, MA, 1991.

Learn How to Use the Simulator

- Computer and tools like simulation have been crucial to the evolution of analog integrated circuit design.
- The problem is the people who use the simulator – there is an unconscious trend to let the simulator do your thinking for you and to assume you know more than you really do.
- In order to use a simulator correctly one needs to realize some simulation “truths”.

Simulation “truths”:

– (Usage of a simulator) x (Common sense) ≈ Constant
– Simulators are only as good as the models and the knowledge of those models by the designer
– Simulators are only good if you already know the answers

Look for Opportunities to Learn

- Seek new challenges rather than staying with what you are comfortable.
- Put yourself in an environment where you can learn from others
- Characteristics of a good company environment:
  - Look for a nucleus of “experts”
  - Development of new products and new fields of opportunity
  - Training programs
  - Concern for your professional development
  - Mentoring opportunities
- Look for opportunity to change jobs if you feel you are stagnating professionally
- Maintain balance in your professional and personal life

A Project to Enhance Productivity of Analog IC Designers

Global Objective: To take 40 years of experience of teaching analog circuit design and use this foundation to create the means of understanding and enhancing this practice in others.

The specific objectives of this project are to:

1.) Enable new and experienced analog IC designers to understand the key principles, concepts and techniques for designing analog circuits in an integrated technology.

2.) Provide experienced analog IC designers with the tools and ability to mentor inexperienced designers.

3.) Teach the key principles, concepts and techniques by a progression of well-planned and executed analog integrated circuit designs in modern CMOS technology.

Project Steps

1.) Development of a short course with the following ingredients

- a.) Technology
- b.) Models
- c.) Electrical Design
- d.) Physical Design
- e.) Testing and Design Capture

2.) Development of six examples of analog circuit design starting from specifications and ending with testing and documentation.

- a.) Stable Voltage Reference
- b.) Operational Amplifier
- c.) Filter
- d.) Analog-Digital Converter
- e.) Voltage-Controlled Oscillator (LC)
- f.) Frequency Synthesizer

3.) Incorporation of the above two items into a short course whose focus is to teach an understanding of how analog IC design is performed.

4.) After the short course has been tested and refined, write the results in the form of a text on the practice of analog IC design.

Mentoring/Coaching

Goal: Apply the previous material in a mentoring/coaching environment to help experts in industry apprentice new engineers.

Problem: Capable mentors do not know how to teach others.

- The process by which they became "experts" is not clear, only that they are or are considered to be.
- In one sense, many "experts" are more on the "art" side of analog design than the "science" side

Solution: Help these "experts" become more aware of the "science" of analog design

- Identify the key principles, concepts and techniques (PCT)
- Illustrate the PCT
- Illustrate the techniques of mentoring – What is it? How is it done? How much time does it take?
- The principle of doubling (may take 3-4 possible mentors to get 2 real mentors)

Problem: Some capable mentors do not have the people skills to teach others.

Solution: Difficult to solve. Requires humility and teachability.

SUMMARY

- What is analog circuit design?

  The complex process of creating circuit solutions using analog circuit techniques.

- What is the analog integrated circuit design process?

  The even more complex process of combining analog design with IC technology which requires electrical, physical and test design.

- What are the key principles, concepts and techniques for analog IC design?

  Key principles – Fundamental laws

  Key concepts – Important relationships and ideas

  Key techniques – Tools that allow simplification or insight

- How can the analog IC designer enhance creativity and solve new problems in today's industrial environment?

  Learn the key principles, concepts and techniques of analog circuit design

  Learn from mistakes

  Learn the technology

  Always try to understand the concept and operation of the circuit, never rely on a computer or someone else for this understanding