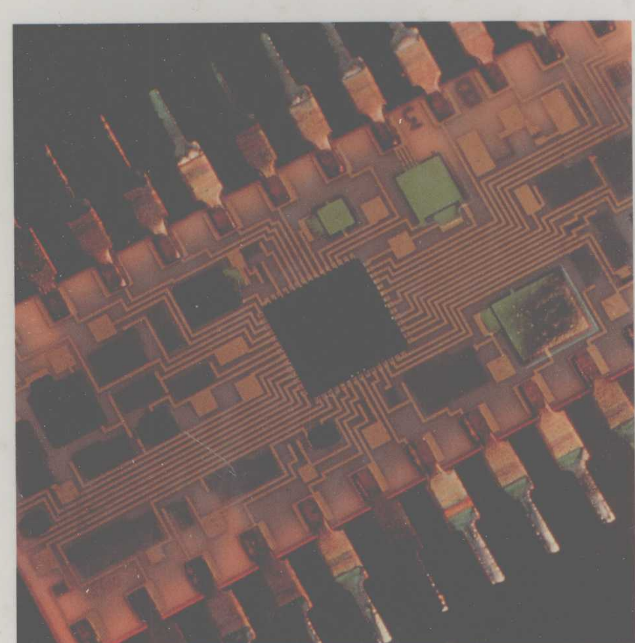
INTRODUCTION TO DIGITAL MICROELECTRONIC CIRCUITS



GOPALAN

INTRODUCTION TO DIGITAL MICROELECTRONIC CIRCUITS

K. "Gopal" Gopalan
Purdue University Calumet

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To
Kalaichelvi,

Ilango,
and
Elil
for their
love, understanding, and support

எப்பொருள் யார்யார்வாய்க் கேட்பினும் அப்பொருள்
மெய்ப்பொருள் காண்ப தறிவு.

To discern the truth in everything heard from whomsoever is knowledge.
Thirukkural, Chapter 42, Verse 3
Thiruvalluvar, Tamil Sage, 35 B.C.

PREFACE

Of all the new technologies that have evolved in the last few decades, perhaps the digital integrated circuit (IC) technology is the one that continues to experience a phenomenal growth in terms of overall circuit complexity, switching speed, and power dissipation. This growth has created a pivotal place for teaching digital electronics in the undergraduate electrical and computer engineering curricula. The vast amount of material arising from innovative circuit designs and newer device technologies, however, requires that the circuit analysis aspects of digital electronics be covered in a first course, separated from device design and chip layout considerations. While the chip level design and layout are important in the design of Very Large Scale Integration (VLSI) systems and Application-Specific Integrated Circuits (ASIC), clear understanding of the performance characteristics of available devices is required for designers of systems using 'off the shelf' ICs. Therefore, the pedagogical approach taken in this book is to cover the analysis and performance comparison of different gate level logic circuits. Since the logic design course covers the building block implementation of a digital system, it is appropriate that the digital electronics course consider the analysis aspects of these building blocks arising from different technologies, primarily at the circuit level. A strong background in the analysis and comparative strengths of available technologies, from the circuits point of view, is required to make practical design trade-offs. For a systems architect interested in developing noncustomized systems by interconnecting standard ICs, such a background can be readily developed in a course without the chip or the physical level of design. Furthermore, with newer IC technologies appearing every few years, a thorough treatment cannot be given in a single course covering both the technologies and the circuit designs. Finally, the availability of computer-aided VLSI design tools still requires the user of these tools to choose the appropriate technology based on the requirements of a given application. Thus, the circuit level analysis provides an appreciation of the circuit design techniques and equips students for the efficient design of digital systems.

Subscribing to this philosophy of analyzing digital circuits in a single course, *Introduction to Digital Microelectronic Circuits* covers the basic gates in all of the presently available logic families. In addition, circuit configurations for VLSI implementation, interfacing of logic families, regenerative logic circuits, analog-digital interfacing, semiconductor memories, and programmable logic devices are discussed. Where applicable, design examples based on logic level requirements are presented.

MicroSim™ PSpice® simulation of the logic families is emphasized throughout the book. PSpice is chosen because of its availability and convenience compared to other simulation tools. Since the basic logic circuits in each family typically have no more than 10 transistors, the student version of MicroSim PSpice, available at no cost from MicroSim, can readily handle the analysis. It has been the author's experience that with PSpice and personal computers, students tend to complete the simulation of a circuit and analyze the results more conveniently, and also better appreciate the importance of simulation.

Emphasis is placed on the analysis of IC gates available in the market in each logic family, while theoretical circuit configurations are considered only as possible examples.

With this emphasis and the laboratory experiments using IC and discrete (simulated) versions of gates from each family, students gain insight into the relative merits of different circuit configurations in each of the logic families studied.

KEY FEATURES

Every attempt has been made to offer a distinctive perspective on the subject of digital microelectronic circuits. In particular, this book:

- Develops the study of semiconductor devices and digital electronics for students with a background in basic circuit analysis and some exposure to physics and electronics.
- Presents a complete treatment of the analysis of bipolar logic gates, from the early RTL to the popular TTL families and the advanced Schottky TTL families.
- Provides comprehensive coverage of the basic, 10K, 10KH and 100K series of ECL gates, and the I^2L gates.
- Explains thoroughly the implementation of logic gates using different configurations of MOS devices.
- Extends the analysis of digital IC families to cover the more recent BiCMOS and GaAs technologies.
- Gives a balanced treatment of regenerative logic circuits using bipolar and MOS discrete and integrated circuits.
- Includes coverage of popular methods of analog-digital data conversions.
- Introduces LSI and VLSI systems with memories and gate arrays.
- Incorporates MicroSim PSpice modeling and simulation throughout.

ORGANIZATION AND OUTLINE OF CHAPTERS

The book is organized into 10 chapters. Each chapter begins with an introduction and ends with a summary of key points covered, references, review questions, problems, and experiments. End-of-chapter problems serve as exercises, and are also used frequently to illustrate and/or extend some of the concepts presented in the text. Problems requiring computer simulation for analysis or design verification and those involving lengthy calculations are indicated by *. Experiments at the end of each chapter are used to extract device parameters for readily available bipolar and MOS devices and to provide an understanding of the performance characteristics of basic logic circuits using these devices.

Chapter 1 outlines the basic steps in the design of a digital system, and the importance of analyzing a system at various levels of design. Ideal and practical logic inverter characteristics are presented.

Fundamentals of semiconductors and current conduction mechanisms are described in Chapter 2. Operation and modeling of junction diodes are discussed.

Chapter 3 gives a brief description of the structure and operation of bipolar junction transistors (BJTs). Ebers-Moll, hybrid-π, charge-control, and MicroSim PSpice models are presented.

Static and dynamic characteristics of BJT saturation logic families are analyzed in Chapter 4. Performance improvements of different TTL families are compared.

Chapter 5 presents the analyses of different current mode logic families and their implementations in large-scale integration systems. Interfacing of saturation and current mode logic families is studied.

Chapter 6 provides a brief description of the structure and operation of MOSFETs and MESFETs. Simplified models for hand calculations and MicroSim PSpice models are presented for these devices.

Analyses of different structures of MOSFETs, BiCMOS, and gallium arsenide MESFET logic circuits are treated in Chapter 7. Interfacing of BJT and MOS logic families is discussed.

Multivibrator circuits as a class of sequential circuits are analyzed in Chapter 8. Both discrete and integrated circuit implementations using bipolar and MOSFET devices are considered.

Chapter 9 presents various analog-digital conversion techniques.

Chapter 10 provides an introduction to the implementation of bipolar and MOS memories. Different programmable logic devices are discussed as examples of VLSI systems.

AUDIENCE

This text is intended for a one-semester, upper-level undergraduate course in electrical and computer engineering.

Basic knowledge of circuit analysis at the level of a first engineering circuit analysis course is assumed. Introductory level of knowledge in semiconductors and electronics is helpful, but not required. Enough material, however, is included to cover logic device characteristics, currents in semiconductors, and the structure, characteristics, and models of diodes, BJTs, and the FETs. Additionally, a concurrent (or previous) course in digital logic fundamentals is helpful.

Most of the material in this text has been used at Purdue University Calumet in a one-semester, upper-level course. The course is required for computer engineering and optional for electrical engineering students with a background in basic analog electronic circuits at the diode, BJT, and FET level. With two hours of lecture and three hours of laboratory per week, all the chapters are covered at least partially. A minimum of 12 laboratory experiments covers the characteristics of devices, logic families, multivibrators, and data converters. Most of the experiments require students to determine the performance characteristics of logic families in the lab and compare them with calculated and simulated results.

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INTRODUCTION

This chapter provides the motivation for the analysis and design of digital microelectronic circuits. Digital systems are used extensively in all realms of modern life. We find them in applications ranging from home appliances, entertainment systems, and palmtop computers to health care products, high-speed computers, and communication systems. More and more applications using digital techniques appear every year, with high precision, small size, and low power dissipation. Analysis of digital electronic circuits is vital to understanding present technologies of microelectronic circuits and to designing these digital systems at all levels of integration. This chapter outlines the design steps and emphasizes the use of computer-aided tools for the analysis and design of complex digital systems. As a first step in the analysis of digital electronic technologies, we examine the performance characteristics of general inverters.

1.1 DIGITAL SYSTEMS

Digital systems operate on information, or data, represented in discrete form. The most common discrete form used is the *binary,* with two disjoint sets of voltage levels representing binary low (0) and high (1) states. With each voltage level constrained to vary within a specified range, the output of a digital system is predictable over a wide range of operating conditions. Other advantages of digital systems over analog, or linear, systems (in which information is represented by continuously varying voltages or currents) include low cost, easy extension of data size, long-time storage capability, and programmability.

Digital systems use electronic circuits that operate, most commonly, as switches, with open switch position designated as logic, or binary, 1 (or high), and closed position as 0 (or low). Alternatively, the output of a digital electronic circuit may be one of two well-defined ranges of voltages (or currents) for the two logic states. Semiconductor diodes and transistors are used as switching devices in digital systems, also called *logic* or *switching* systems. *Microelectronics* refers to the technology of fabricating a large number of electronic devices on a single chip of silicon or a compound semiconductor material such as gallium arsenide. The size of the active transistor area in chips has progressively decreased to about 0.1 μm^2 at present, while a density of over a million transistors is achieved in an overall chip size of less than 100 mm^2 [1, 2]. Compare this area and density with those of the chips available at the beginning of the integrated circuit era, circa 1966: a chip area of approximately 5 mm^2, for example, contained 50 active devices with areas of about 0.025 mm^2 each [3]. Simultaneous with high density, high operating speeds of close to a billion operations per second, and high data transfer rates of nearly 10 Gbits/s have recently been achieved. This remarkable increase in performance along with decrease in size is due primarily to advances in the technology of the semiconductor device fabrication process, and to the development of innovative circuit configurations.

In the following section we consider the steps in the design of a digital system.

1.2 DESIGN OF DIGITAL SYSTEMS

Design of a digital system, be it a simple traffic light control system or a complex high-speed computer, proceeds with the following general steps: *specification, functional design,* detailed *logic design,* and *fabrication and testing.* As we will see, for the more complex of these applications, two more steps may also be needed before the final fabrication step.

As with any system, the first step in the design is the detailed specification of the requirements of the system. In this step, the design engineer determines the required number and voltage levels of inputs and outputs, speed of performance, range of power supply, physical size, and operating environment.

The next step is to create a functional model of the system. At this phase, the system is described in terms of abstract blocks, which, when interconnected, simulate the intended behavior for the given input and initial conditions. The goal in this phase is to establish the required building blocks and their interconnections to meet the gross operational specifications of the system. This step is also called the *architecture,* or *register level* design, particularly when referring to computer design. The design at this step represents the behavioral, or input-output, model of the system. Currently, we describe and specify the behavioral model in an abstract language such as Verilog or VHDL.[1]

In the next step, the *logic,* or *structural,* design considers how to implement the blocks identified in the functional design stage. While some of the blocks may be available as off-the-shelf components, others must be realized from basic elements. A divide-by-N counter, or an N bit sequence detector, for example, may not be available directly for any given value of N. A logic designer carries out the logic design of such blocks in this phase, as well as the interfacing of each block with others, if necessary. This is the primitive level of design, where one chooses the applicable technology for each functional as well as logic block, based on such considerations as power, size, and speed.

[1] Verilog is a registered trademark of Cadence Design Systems, Inc. VHDL, which stands for VHSIC (very high speed integrated circuits) Hardware Description Language, was developed with the sponsorship of the U.S. Department of Defense.

The final step is the fabrication of the blocks in printed circuit boards and performance-testing of the assembled system. In this step, all the blocks identified in the previous steps are interconnected with appropriate power and signal sources. A test engineer validates the completed system by supplying or simulating the specified inputs and monitoring the outputs from the system.

The above process for a system design assumes the use of readily available, off-the-shelf components: at the logic design level, small-scale integration (SSI) circuits for gates and flip-flops, and, at the functional level, medium-scale integration (MSI) circuits such as counters and shift-registers, and, in some cases, large-scale integration (LSI) circuits, such as memory and logic arrays.[2] For a number of applications with low volume, and/or those that will need changes in specifications with time, this design methodology is sufficient. However, the process has several limitations for use in applications where size and power dissipation are also primary considerations. When there are number of different circuits at different integration levels, sizes, power, and cost, these add to the overall cost, power, size, and assembly and testing time. For example, a digital time/temperature display unit or a marquee sign can be built efficiently using SSI, MSI, and LSI components; a wristwatch or a notebook computer, on the other hand, becomes costly and prohibitively large in size, and dissipates a disproportionate amount of power for its application when built with off-the-shelf integrated circuits. In addition, the advantages of high-speed technology at the gate and the functional levels would be lost in the system due to the extensive wiring and interconnection needed. To achieve a more appropriate design for such applications the designer extends the previous design steps from the logic (or *gate*) level of design to the *circuit* level, then the *chip (device) layout* level, and, finally, arrives at chip fabrication. Figure 1.1 shows the complete design steps. Because the final product here is a single chip for a given application, it is an application-specific integrated circuit (ASIC). It is also a very large scale integration (VLSI) circuit if its size exceeds 10,000 equivalent gates.

Unlike in MSI/SSI-level design, VLSI and ASIC circuits have stringent constraints while offering flexibility at the circuit and chip level of design. For example, because of its small size, the number of external pins (connections) in an ASIC or VLSI circuit is limited to a few hundred. As a result, some of the input signals may need to be generated internally, and the number of output lines may be limited. This, in turn, could result in lower performance, increased size, more components, and more design changes. Size is also a significant factor in determining maximum power dissipation within the chip and the operating supply voltage. The functional level design must, therefore, consider size with other specifications. Design at the logic level in ASIC and VLSI circuits must minimize redundancy, to ensure the minimum number of gates and to minimize size. In addition, design at the circuit level—which is the primitive level for a given technology of ASIC or VLSI circuits—must obtain optimum gate circuit

[2] *Generally accepted definitions for scale of integration are: 1 to 10 gates per chip:* SSI; 10 to 100 equivalent gates per chip: MSI; 100 to 10,000 equivalent gates, or memory bits per chip: LSI; and over 10,000 equivalent gates: VLSI (very large scale integration). For chips with a million or more equivalent gates, the term ULSI (ultra large scale integration) is sometimes used. In all these cases, a gate represents the basic block—an inverter, typically—in the given technology.

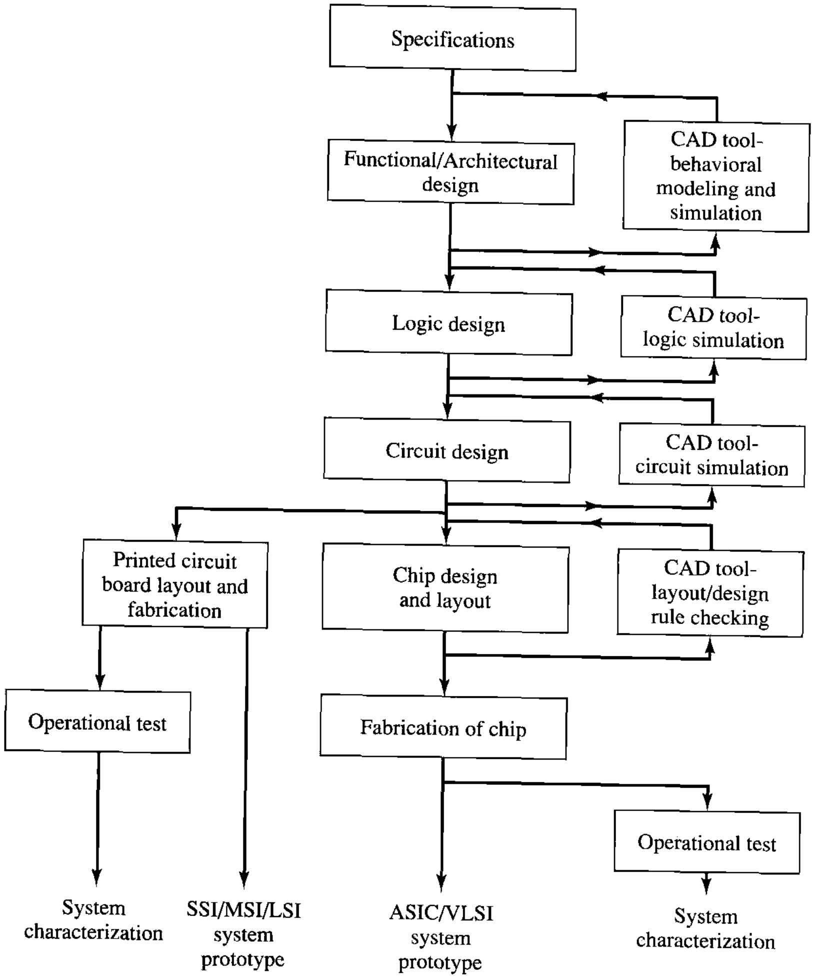

Figure 1.1 Steps in the design of a digital system

configuration in terms of speed, power, and size. Finally, careful layout at the chip level ensures that a compact chip results, with the architecture dsigned at the functional level. Testing of the chip after fabrication verifies that the final circuit meets all of the performance specifications: static, dynamic, power, and environmental.

Because of the interrelationship among the design phases, a digital system design engineer must have expertise in one or more levels and must know enough in all other levels to design and fabricate efficient systems. An architecture for adding N bits of data, for example, may be more efficient using serial addition than parallel addition if the source bits are given serially at a high rate. Therefore, an understanding of the adder implementation at the register level helps the design engineer achieve an efficient design. Similarly, at the logic level, a combination of multiplexers or a programmable logic device might cut down design time and costly layout of different circuit patterns for realizing multiple logic functions in many variables. An innovative circuit design might, on the other hand, reduce size and power or increase speed of operation. With device technology advancing rapidly, the choices of available technology are crucial in determining overall performance and cost. If a design objective is the operation of a digital system at data transfer rates exceeding hundreds of Mbits/s, then a good choice might be Emitter-Coupled Logic (ECL), Bipolar-Complementary Metal-Oxide Semiconductor (BiCMOS), or gallium arsenide Metal-Semiconductor Field Effect Transistor (GaAs MESFET) technology. If, in addition to high speed, the system must dissipate low power, the choice is narrowed to BiCMOS technology, which has operating speeds rivaling that of ECL but at significantly reduced power dissipation. At present, ECL has the highest power dissipation; GaAs MESFET technology, on the other hand, exceeds ECL in speed but is more expensive due to its low yield and has not attained the same level of maturity as other technologies. However, with advances in GaAs device fabrication technology, data rates exceeding Gbits/s have been achieved. Additionally, we have recently seen the development of high density MOS (Metal-Oxide-Semiconductor) implementation of memory devices with storage capacities in the Gbit range. Clearly, these types of developments in technology must be considered in the design of high-speed, high-density, and low-power digital systems.

1.3 ANALYSIS OF DIGITAL SYSTEMS

To develop an error-free digital system in the form of a VLSI circuit, one must verify design at every step. Analysis of the functional level design blocks and their interconnections is necessary to check the input-output logic functionality of the system. Logic level analysis verifies the truth table, state table and/or flow table for each block and identifies timing errors (glitches, races, and hazards).[3] Analysis of basic gate circuits in a given technology presents static and dynamic performance characteristics and helps in devising novel configurations to meet overall design objectives. Verification of chip design is essential in a complex circuit to avoid costly and time-consuming errors when laying out active devices and making interconnections. In addition, layout must be checked for parasitic devices, noise sources and, more frequently, capacitances. Clearly, the top-down design approach has local feedback paths at each level so that problems identified during analysis can be corrected. This type of iterative design based on analysis and feedback is indispensable to meet all the performance specifications of the system and to prevent malfunctioning under all operating conditions. Finally, characterization of the final product by testing under

[3] For a detailed discussion of these topics, the reader is referred to logic design textbooks such as Roth [7] or Wakerly [8].