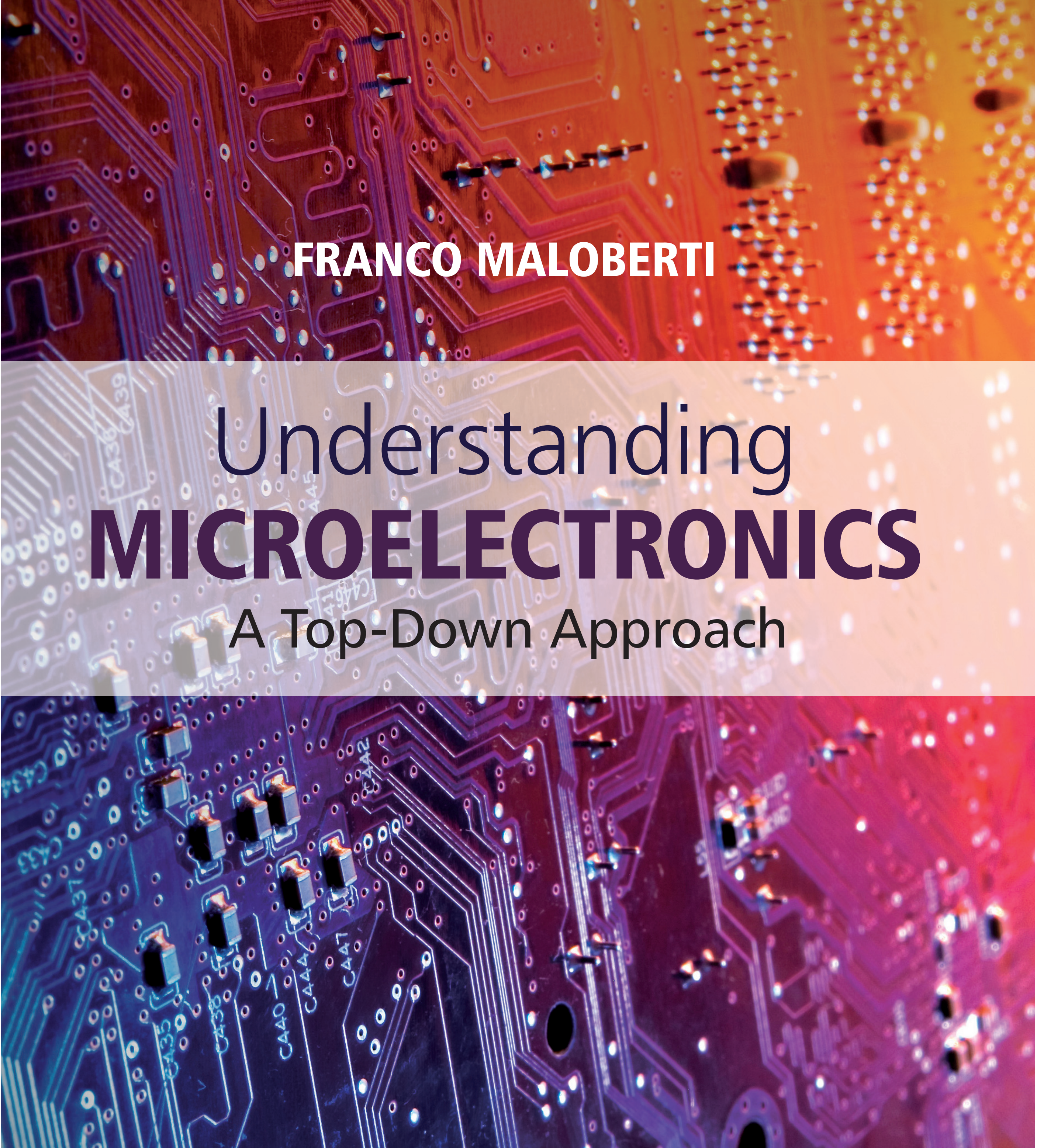

FRANCO MALOBERTI

Understanding MICROELECTRONICS

A Top-Down Approach

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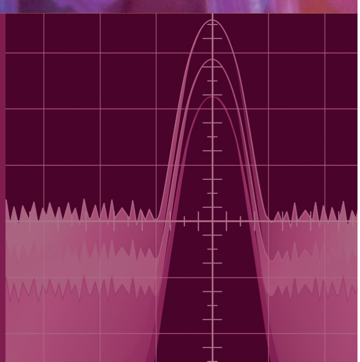

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A Top-Down Approach

Franco Maloberti

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To Pina, Amélie,
Matteo and Luca

And in memory of my
father, Alberto

CONTENTS

Preface

Electronics is a young discipline. It was initiated in 1904 when, after some related inventions, J. A. Fleming conceived the first electronic device: the vacuum tube diode. This is a two-terminal component made by a hot filament (cathode) able to emit electrons in the vacuum. A second electrode, the plate (or anode), collects electrons, causing a flow that depends on the sign and the value of the voltage applied across the terminals. Such a device can conduct current only in one direction (the rectifying effect), but actually cannot fully realize "electronic" functions. Two years later L. Deforest added a third terminal, the grid, and invented the vacuum tube triode. This innovation made possible the development of "electronic" functions, the most important of which is the ability to augment the amplitude of very small electrical signals (amplification). For decades after that, electronic circuits were based on those bulky, power-hungry vacuum tubes, operating with high voltage. These were able to evolve into more sophisticated components by the addition of extra grids to allow better control of the flow of electrons from cathode to anode.

At that time the focus of electronic designers was on being able to connect a few active devices (the vacuum tubes) with a large number of passive components (resistors, capacitors and inductors) to build up a circuit. It was necessary to understand the physical mechanisms governing the devices and to know the theoretical basis of network analysis. In short, the approach was from the physics that provides background knowledge to the design theories that enable circuit design.

The situation was almost unchanged even when William Shockley, John Bardeen and Walter Brattain invented the transistor in 1947. Moreover, the focus still remained on devices and circuits for a couple of decades after the introduction of the Integrated Circuit (IC, an electronic device with more than one transistor on a single silicon die). Then, with time and at an increasing pace, the complexity of electronic systems became greater and greater, with the number of transistors greatly exceeding that of passive components. Nowadays many ICs are made only of transistors, with a total count that approximately doubles every two years. Some digital circuits contain billions of elementary components, each of them extremely small.

The result is that the technology evolution has shifted focus from simple circuits to complex systems, with most attention given to high-level descriptions of the implemented functions rather than looking at specific details. Obviously the details are still important, but they are considered after a global analysis of the architecture and not before. In other words, the design methods moved from a bottom-up to a top-down approach.

There is another relevant change caused by electronic advance: the increasing availability of apparatus, gadgets, communication devices and tools for accurate prediction of events and for implementing virtual realities. The social impact of this multitude of electronic aids is that people, especially new generations, expect to see results immediately without waiting for the traditional phases of preparation, description of phenomena by formal procedures and patient scientific observation. We can say that the practice of studying the correlation between cause and effect is increasingly fading. Fewer and fewer people want to ask "What happened?" They are just interested in immediate outcomes; the link between results and the reasons behind them puzzles people less and less. This obviously can prevent the search for new solutions and the origination of new design methodologies.

This unavoidable cultural shift is not negative in itself, but it reduces the effectiveness of traditional teaching styles. The impatience of students who expect immediate results (and fun) contrasts with the customary methods that start from fundamentals and build specialized knowledge on top of them. This is a natural and positive modern attitude that must be properly exploited in order to favor the professional growth of younger generations. In short, if a bottom-up presentation is not well received, it is necessary to move to a top-down teaching method, and that is what this book tries to do.

The top-down approach is based on a hierarchical view of electronic systems. They are seen as a composition of sub-systems defined generically at the first hierarchy level. Each sub-system, initially considered as a "black box" that just communicates with the external world via electrical terminals, is then detailed step by step, by going inside the "black boxes." That is the method that inspires this book and its organization. In fact, Chapter 1 starts from the top, presenting an overview of the microelectronics discipline and defining goals and strategies for both instructor and student. It is suggested that this short chapter be carefully read, to get the right "feel" and attitude needed for an effective learning process. Chapter 2 deals with signals, the key ingredients of electronic processors. They are represented by time-varying electrical quantities, possibly analyzed in other domains. Emphasis is therefore on the signal representation in time, frequency and z-domain. That chapter is probably one of the most difficult, but having a solid knowledge of the topic is essential, and I do hope that the required efforts will be understood by the reader.

Chapter 3 is on electronic systems. The goal pursued is to describe different applications for making the reader aware of the block diagram and hierarchical processing used in the top-down implementation of electronic systems. Important issues such as system partitioning and testing are introduced. Chapter 4 discusses signal processing. It studies linear and non-linear operation and the method used to represent the results. Signal processing operations are, obviously, realized with electronic circuits, but the focus at this level is just on methods and not on the implementations, circuit features and limits affecting real examples.

Electronic functions realizing signal processing are presented in Chapter 5. The analysis is initially at the "black box" level, because the first focus is on interconnections. The chapter also studies how to satisfy various needs by using analog or digital techniques and ideal elementary blocks. Chapter 6 goes further "down" by describing the use of analog key structures for giving rise to elementary functions. These are the operational amplifier (op-amp) and the comparator. The chapter also discusses the specifications of blocks that are supposed to be a discrete part assembled on printed circuit boards, or cells used in integrated systems.

Transformation from analog to digital (and vice versa) marks the boundary between analog and digital processing. Chapter 7 describes the electronic circuits needed for that: the A/D and the D/A converter. The chapter deals with specifications first, and then studies the most frequently used conversion algorithms and architectures. Because of the introductory nature of this book, the analysis does not go into great detail. However, study of it will give the student the knowledge of features and limits that enables understanding and definition of high-level mixed-signal architectures.

Chapter 8 deals with digital processing circuits. As is well known, digital design is mainly performed with microprocessors, digital signal processors, programmable logic devices and memories. These are complex circuits with a huge number of transistors, fabricated with state-of-the-art technology. The majority of electrical engineers do not design such circuits but just use them. Thus the task is mainly one of interconnecting macro functions and programming software of components that are known at the functional level. In the light of this, the chapter describes general features and does not go into the details of complicated architectures. The study is thus limited to introductory notions as needed by users. More specific courses will "go inside." Memories and their organization are also discussed.

Study of the first eight chapters does not require any expertise at the electronic device level. Now, to understand microelectronics further it is necessary to be aware, at least at functional levels, of the operating principles of electronic devices. This is done in Chapter 9, which analyzes diodes, bipolar transistors and CMOS transistors. This chapter is not about the detail of physics or technology. That is certainly needed for fabricating devices and integrated circuits, but not for using them. Therefore, the description given here is only sufficient for the understanding of limits and features that is required by the majority of professional electronic engineers. The elements given, however, are a good introduction to the specialized proficiency needed for IC design and fabrication.

The next two chapters use basic devices to study analog and digital schemes at the transistor level. The goal, again, is not to provide detailed design expertise, because integrated circuits implement functions at a high level. What is necessary is to be familiar with basic concepts (such as small signal analysis) and to know how to handle simple circuits. It is supposed that more detailed study, if necessary, will be done in advanced and specific courses. Chapters 10 and 11 reach the lowest level of abstraction studied in this book. It does not go further down, to a discussion of layout and fabrication issues. Those are the topics studied in courses for integrated circuit designers.

Feedback is introduced in Chapter 12. This topic is important for many branches of engineering. The chapter does not consider specialized aspects but just gives the first elements and discusses basic circuit design implications.

In Chapter 13 the basics of power conversion and power management are presented. This seemingly specialized topic was chosen for study because a good part of the activity of electrical engineers concerns power and its management. Supply voltages must always be of suitably good quality and must ensure high efficiency in power conversion. Power is also very important in portable electronics, which is now increasingly widespread. The topic, possibly studied in more detail elsewhere, analyzes rectifiers, linear regulators and DC–DC converters. At the end the chapter also describes power harvesting, a necessity of autonomous systems operating with micro-power consumption.

The last chapter describes signal generation and signal measurements. This is important for the proper characterization of circuits whose performance must be verified and checked so as to validate design or fabrication. Since sine wave signals are principally used for testing or for supporting the operation of systems, methods for generating sine waves are presented. Features and operating principles of key instruments used in modern laboratories are also discussed.

That is, concisely, the outline of the book. However, we must be aware that an important aid to the learning process is carrying out experiments. This is outlined by the saying: "If we hear, we forget; if we see, we remember; if we do, we understand." Unfortunately, often, offering an adequate experimental activity is problematic because of the limited resources normally available in universities and high schools. In order to overcome that difficulty this book proposes a number of virtual experiments for practical activity. The tool, named ElvisLab (ELectronic VIrtual Student Lab), makes available a virtual laboratory with instruments and predefined experimental boards. Descriptions of experiments, measurement set-ups and requirements are given throughout the book. A demo version of this tool is freely available on the Web with experiments at www.wiley.com/go/maloberti_electronics. ElvisLab provides an environment where the student can modify parameters controlling simple circuits or the settings of signal generators. That operation mimics what is done with a prefabricated board in the laboratory. The tool is intended as a good introduction to such experimental activity, which could also be performed in real sessions, provided that a laboratory and the necessary instruments are available.

The combination of this text and the virtual laboratory experiments is suitable for basic courses on electronics and microelectronics. The goal is to provide a good background to microelectronic systems and to establish by a top-down path the basis for further studies. This is a textbook for students but can also be used as a reference for practicing engineering. For class use there are problems given in each chapter, but, more importantly, the recommended virtual experiments should enable the student to understand better.

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F. Maloberti
Pavia
May 2011

List of Abbreviations

µP Microprocessor
ΣΔ Sigma–Delta
AC Alternating Current
A/D Analog-to-digital
ADC Analog-to-digital converter
ALU Arithmetic Logic Unit
ASIC Application-Specific Integrated Circuit
ATE Automatic Test Equipment
Auto-ID Automatic Identification Procedure
A/V Audio/video
BB Base-Band
BER Bit-Error-Rate
BJT Bipolar Junction Transistor
BWA Broadband Wireless Access
CAD Computer-Aided Design
CAS Column Access Strobe
CCCS Current-Controlled Current Source
CCVS Current-Controlled Voltage Source
CMRR Common-Mode Rejection Ratio
CMOS Complementary MOS
CPLD Complex Programmable Logic Device
CPU Central Processing Unit
D/A Digital-to-analog
DAC Digital-to-analog converter
DC Direct Current
DDS Direct Digital Synthesis
DEMUX Demultiplexer
DFT Discrete Fourier Transform
DLP Digital Light Processing
DMD Digital Micromirror Device
DNL Differential Non-Linearity
DR Dynamic Range
DRAM Dynamic Random-Access Memory
DSP Digital Signal Processor
DVD Digital Video Disc
EDA Electronic Design Automation
EPROM Erasable Programmable Read-Only Memory
EEPROM Electrically Erasable Programmable Read-Only Memory
ESD Electrostatic Discharge
ESR Equivalent Series Resistance
FF Flip-flop
FFT Fast Fourier Transform

FIR Finite Impulse Response
FM Frequency Modulation
FPGA Field Programmable Gate Array
GAL Generic Array Logic
GBW Gain Bandwidth Product
GE Gate Equivalent
GSI Giga-scale Integration
HD2 Second Harmonic Distortion
HD3 Third Harmonic Distortion
HDD Hard Disk Drive
HDL Hardware Description Language
HTOL High Temperature Operating Life
IC Integrated Circuit
IEEE Institute of Electrical and Electronics Engineering
IF Intermediate Frequency
INL Integral Non-Linearity
IP Intellectual Property
I/O Input/Output
ISO International Organization for Standardization
I–V Current–Voltage
JFET Junction Field-Effect Transistor
JPEG Joint Photographic Expert Group
LCD Liquid Crystal Display
LDO Low Drop-Out
LED Light-Emitting Diode
LNA Low Noise Amplifier
LSB Least Significant Bit
LSI Large-Scale Integration
LUT Look-Up Table
Mbps MegaBit Per Second
MEMS Micro Electro-Mechanical Systems
MIM Metal–Insulator–Metal
MIPS Mega Instructions Per Second
MMCC Metal–Metal Comb Capacitor
MOS Metal–Oxide–Semiconductor
MPGA Metal-Programmable Gate Array
MRAM Magneto-resistive RAM, or Magnetic RAM
MSI Medium-Scale Integration
MS/s Mega-Sample per Second
MUX Multiplexer
NMH Noise Margin High
NMH Noise Margin Low
NMR Nuclear Magnetic Resonance
NRE Non-Recurrent Engineering
OLED Organic Light-Emitting Diode
op-amp Operational amplifier
OSR Oversampling Ratio
OTA Operational Transconductance Amplifier
PA Power Amplifier
PAL Programmable Array Logic
PCB Printed Circuit Board
PDA Personal Digital Assistant
PDIL Plastic Dual In-Line
PDP Plasma Display Panel
PFD Phase-Frequency Detector
PLD Programmable Logic Device
PLL Phase-Locked Loop
PMP Portable Media Player
POS Product-of-Sums
ppm Parts per Million
PROM Programmable Read-Only Memory
PSRR Power Supply Rejection Ratio
PSTN Public Switched Telephone Network
R/C Remote-Controlled (toys etc)
RAM Random-Access Memory
RAS Row Address Strobe
RC Resistor-Capacitor
RF Radio Frequency
RFID Radio Frequency IDentification
RMS Root-Mean-Square
ROM Read-Only Memory
RPM Revolutions Per Minute
R/W Read/Write
Rx Reception
S&H Sample-and-Hold
SAR Synthetic Aperture Radar
SAR Successive Approximation Register (Chapter 7)
SC Switched Capacitor
SDRAM Synchronous Dynamic Random-Access Memory
SFDR Spurious Free Dynamic Range
SiP System-in-Package
SLIC Subscriber Line Interface Circuit
SNDR Signal-to-Noise plus Distortion Ratio
SNR Signal-to-Noise Ratio
SoC System-on-Chip

SoP Sum-of-Products
SPAD Single Photon Avalanche Diode
SRAM Static Random-Access Memory
SSI Small-Scale Integration
T&H Track-and-Hold
THD Total Harmonic Distortion
Tx Transmission
USB Universal Serial Bus
USI Ultra Large-Scale Integration
UV Ultraviolet
VCCS Voltage-Controlled Current Source
VCIS Voltage-Controlled Current Source
VCVS Voltage-Controlled Voltage Source
VCO Voltage-Controlled Oscillator
VCVS Voltage-Controlled Voltage Source
VLSI Very Large-Scale Integration
VMOS Vertical Metal–Oxide–Silicon
WiMAX Worldwide Interoperability for Microwave Access
WLAN Wireless Local Area Network
X-DSL Digital Subscriber Line

CHAPTER 1

OVERVIEW, GOALS AND STRATEGY

> Bodily exercise, when compulsory, does no harm to the body; but knowledge that is acquired under compulsion obtains no hold on the mind.
>
> —Plato

1.1 GOOD MORNING

I don't know whether now, the first time you open this book, it is morning, afternoon, or, perhaps, night, but for sure it is the morning of a long day, or, better, it is the beginning of an adventure. After a preparation phase, this journey will enable you to meet electronic systems, will let you get inside intriguing architectures, will help you in identifying basic functions, will show you how electronic blocks realize them, and will give you the capability to examine these blocks made by transistors and interconnections. You will also learn how to design and not just understand circuits, by using transistors and other elements to obtain electronic processing. Further, you will know about memories used for storing data and you will become familiar with other auxiliary functions such as the generation of supply voltages or the control of accurate clock signals. This adventure trip will be challenging, with difficult passages and, probably, here and there with too much math, but at the end you will, hopefully, gain a solid knowledge of electronics, the science that more than many others has favored progress in recent decades and is pervading every moment of our lives.

Understanding Microelectronics: A Top-Down Approach, First Edition. Franco Maloberti.

If you are young, but even if you are not as old as I am . . . (well, don't exaggerate: I have white hair, I know, but I am still young, I suppose, since I look in good shape). If you are young, I was saying, you have surely encountered electronics since the first minute of your life. Electronic apparatus was probably used when you were born, and even before that, when somebody was monitoring your prenatal health. Then you enjoyed electronics-based toys, and you have used various electronic devices and gadgets, growing in complexity with you, many times a day, either for pleasure or for professional needs, ever since. Certainly you use electronics massively and continuously, unless you are shipwrecked on a faraway island with just a mechanical clock and no satellite phone, with the batteries of your MP3, Personal Digital Assistant (PDA), tablet or portable computer gone, and no sophisticated radio or GPS.

Well, I suppose you have already realized that electronics pervades the life of everybody and aids every daily action, and also, I suppose, you assume that using electronics is not difficult; electronic devices are (and must be) user friendly. Indeed, instruction manuals are often useless, because everybody desires to use a new device just by employing common sense. People don't have the patience to read a few pages of a small multilingual booklet. Moreover, many presume that it is useless to know what is inside the device, what the theoretical basis governing the electronic system is and what its basic blocks and primary components are, and, below this, to know about the materials and their physical and chemical properties. In some sense, an ideal electronic apparatus is, from the customer's point of view, a black box: just a nicely designed object, intuitive to operate and capable of satisfying demanding requests and expectations.

What do you expect from a microelectronic system?

I suppose, like everybody else, you expect to be able to use the system by intuition without reading boring instruction manuals, to have an answer to your request for high performance, and to pay as little as possible.

Indeed, it is true that modern electronic equipment is user friendly, but, obviously, to design it, to understand its functions in detail, and, also, to comprehend the key features, it is necessary to have special expertise. This is the asset of many professionals in the electronics business: people who acquire knowledge up to a level that gives the degree of confidence they need so as to perform at their best in designing, marketing, promoting, or selling electronic circuits and systems.

Therefore, we (you and I) are facing the difficult task of transforming a user of friendly electronics or microelectronics into an expert in microelectronics. For that, it is necessary that you, future electronics professional, open (and this is the first obstacle), read, and understand a bulky book (albeit with figures) printed on old-fashioned paper. This is not easy, because anyone who uses a computer and the Web is accustomed to doing and knowing without feeling the need to read even a small instruction manual.

I have to admit that the method followed for decades in teaching scientific and technical topics is perceived as out of date by most modern people. I am sure you think that starting from fundamentals to construct the building of knowledge, step by step, is really boring! There are quicker methods, I assume you think. Indeed, following the traditional approach requires one to be very patient and not to expect immediate results as with modern electronic aids. Nevertheless, it is essential to be aware that fundamentals are important (or, better, vital). It is well known that a solid foundation is better than sand: a castle built on sand, without foundations, will certainly collapse. That is what old people usually say, but, again, studying basic concepts is tedious. So what can I do to persuade you that fundamentals are necessary?

Perhaps by narrating a tale that I spontaneously invented many years ago during a debate at a panel discussion. That tale is given here.

The man who owned 100 cars

A rich man was so rich that he owned 100 cars, one for every moment of his life, with three drivers per car available 24 hours a day. The drivers' job included unrolling a red carpet on the small paths from one car to the next and having every car available every moment of the day and night. One marvelous day the wife of the rich man gave birth to a beautiful child. This brought great happiness to the man, his wife and the 300 drivers of the 100 cars.

Two years later, as the second birthday of the lovely boy approached, it was time to decide on the birthday present and the rich man already had thought of a small car with golden wheels. He asked his wife: "*What do you think?*". The lady promptly replied: "*I would prefer a pair of shoes.*" "*What?*" cried the man, "*I have 100 cars and miles of red carpet! My son does not need to walk! Shoes are for the poor people that have to walk.*"

After the panel, when the discussion was over, a colleague of mine approached me, saying: "Excellent! You exactly got the point. Fundamentals are essential. You are right; having cars does not justify bare feet." He fully agreed with me, and certainly liked the way I described the need to know fundamentals even if powerful tools are available for helping designers.

The risk is that computer tools, embedding overwhelming design methods, favor the habit of trying and retrying until acceptable results are obtained. Therefore computer support often gives rise to results that appear very good without requiring the hard intellectual work that is supported and favored by a solid technical background.

Indeed, fundamentals are essential, but knowing everything is negative: it is necessary to settle at the right level. Saturating the mind by a flood of notions creates too many mindsets and, consequently, limits creativity. A discussion on creativity would take pages and pages, and I don't think this is the proper place to have it. However, remember that a bit of creativity (but not too much) is the basis for any successful technical job. Blending basic knowledge, creativity, quality, and execution must be the goal. This makes the difference between a respected (and well paid) electronic engineer and a pusher of keys.

Remember that anybody is able to push buttons, so becoming a key pusher does not add much to professional capability. Even a monkey can do that! So, the key point is: *where is the* *added value? What makes the difference?* Obviously, for a successful future, it is necessary to acquire more than the capability of pushing buttons. For this, computer-aided tools should not be used for avoiding thought but for improving the effectiveness of the learning process. This is very important, and, actually, the goal of this book is to provide, with a mix of fundamentals and computer-aided support, the basis of that added value that distinguishes an expert.

Now, I think that is enough introduction, and after this long discussion (it may be a bit boring) I suppose that you, my dear reader, are anxious to see the next step. So, ... let's organize the day. And, again, good morning.

1.2 PLANNING THE TRIP

When planning an adventurous trip, for safety and to ensure your future enjoyment it is recommended that you check a number of points. First, you have to define the trip in terms of a wish list; for example, you need to define whether you want to camp out at night, bunk in a rustic hut or stay in a five-star hotel. Also, you need to state whether you plan to stop in a small cafe and chat with local people or whether you desire to visit a museum. For this special adventurous trip, I suppose your wish list includes:

- the desire to become an expert on electronic systems, to know their basic properties, to be able to assess them and to recognize their limits;
- the wish to know more about the signals used and processed in electronic systems so as to understand whether a parameter value is good or bad and to learn how to generate test signals and use them for performance verification;
- the ability to read circuit diagrams so as to see, possibly at a glance, where the critical points are and to estimate expected performance;
- the desire to know about the basic blocks used in a system, to optimize the key performances by using computer simulation tools and to know how to interconnect those blocks so as to obtain given processing functions;
- the willingness to know in detail how transistors work and to learn the modern integrated technologies used to realize transistors and integrated circuits;
- curiosity about modeling transistors and the physical and chemical basic principles underlying their fabrication.

Well, I am not sure that all the above points are your goals, but, frankly, even a subset of them is a bit ambitious and will surely require significant efforts to achieve. But don't be discouraged. After the initial steps the path will be more and more smooth, and with the help of this book you will (hopefully) obtain good results.

After deciding on the type of trip (device oriented, integrated circuit oriented, system oriented, or another type), it is necessary to verify that you are in the proper shape to enjoy the experience. For this, there are a number of requisites that are essential. The most relevant are:

- a reasonable mathematical background with the ability to solve first- and second-order differential equations;