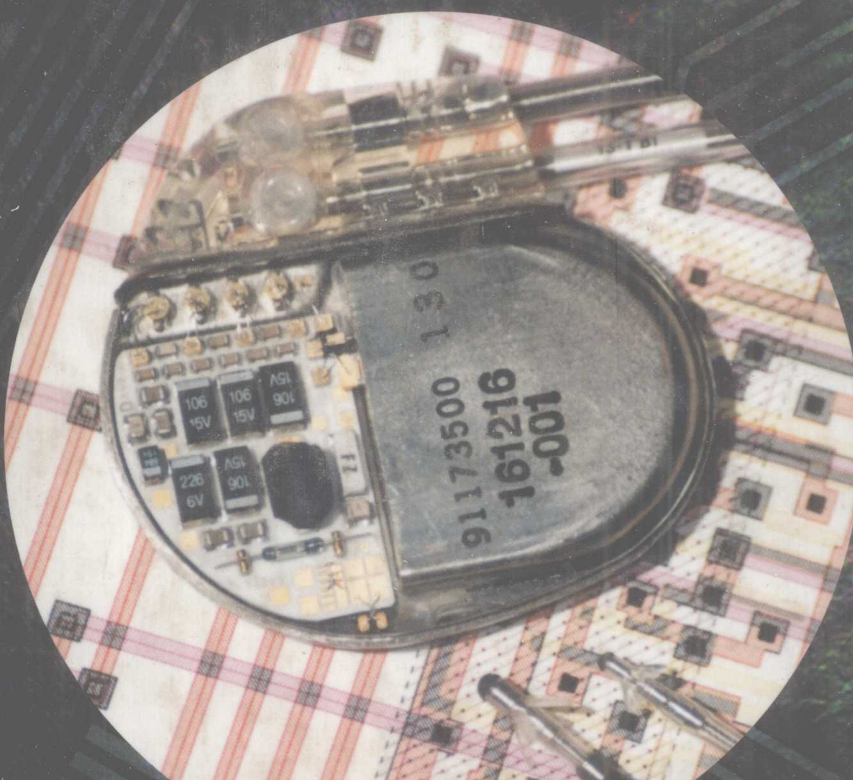
Electronics

SECOND EDITION



ALLAN R. HAMBLEY

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Second Edition

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Preface

This book is intended for use in the core electronics courses for undergraduate electrical and computer engineering majors. The book frequently takes the designer's point of view in discussing circuits, illustrates design with numerous examples, shows how to test circuit designs using SPICE, and provides numerous open-ended design problems with which students can practice.

WHAT'S NEW IN THE SECOND EDITION

1. The entire book has been reorganized and rewritten with an eye toward reducing its length and making it more student friendly.
2. Integrated-circuit techniques are treated earlier and receive greater emphasis throughout.
3. The needs of computer-engineering students are addressed by treating the switching behavior of devices early in the book, adding a chapter on CMOS logic circuits, and adding a discussion of data converters.
4. Several motivational examples are provided in the "Anatomy of a Design" sections as asides from the main text to show how interesting circuits can be designed using the material learned to that point in the book. For example just after the chapters on op-amps and diodes, the design of a function generator is illustrated.
5. The introduction and the treatment of external amplifier characteristics have been condensed into the first chapter.
6. MOSFETs are emphasized over JFETs.
7. Op-amps are treated in a single chapter.
8. The treatment of device physics has been shortened and appears in the various chapters on an as needed basis.
9. The chapter on SPICE has been eliminated because most students learn to use SPICE in their circuits courses.

ASSUMED BACKGROUND AND LEVEL OF PRESENTATION

The background assumed is a first course in circuit analysis. In the beginning, the level of presentation is appropriate for an introductory core course. Starting with Chapter 7, the level gradually increases to that appropriate for juniors having a stronger interest in the subject. Circuit analysis by Laplace transform methods is helpful (but not required) background for frequency response and compensation of feedback amplifiers in Chapter 9.

INSTRUCTIONAL AIDS

A website located at http://www.prenhall.com/hambley contains a number of resources for instructors and students including:

- Answers to selected end-of-chapter problems
- PDF files of key figures from the book that can be used to make transparency masters
- Schematic files for the circuits discussed in the book
- Schematic files that are the answers to Exercises that call for SPICE analysis
- A selection of links to manufacturers' sites where additional data may be downloaded

A solutions manual containing complete solutions for the exercises and problems is available to instructors who adopt the textbook for classroom use. To obtain a copy, contact your local Prentice Hall sales representative or write to the publisher on your school letterhead. The address of the publisher is:

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CONTENT

This book supports a wide variety of course plans. More than enough material is provided for a two-semester (or three-quarter) course sequence, allowing topic selection suited to the interests of the instructor and students.

Chapter 1 contains an overview of electronics and treats the external characteristics of amplifiers. The first several sections acquaint students with the big picture and illustrate how the details studied in this book fit into that picture. Usually, I assign this material for reading but don't spend class time on it. Next, we introduce basic amplifier concepts including gain, input resistance, output resistance, frequency response, and circuit models for amplifiers. The chapter concludes with a discussion of differential amplifiers, setting the stage for op-amps.

Chapter 2 treats operational amplifier circuits including basic amplifiers, imperfections of op-amps, integrators, and differentiators. The discussion of amplifiers gives immediate application for the concepts (that were introduced in Chapter 1) of gain, input resistance, output resistance, and ideal amplifier types.

Chapter 3 treats diodes and diode circuits, including load lines, ideal diodes, rectifiers, wave shapers, logic circuits, voltage regulators, device physics, and switching behavior. The small-signal-equivalent-circuit concept is introduced in Section 3.8 setting the stage for BJT and FET amplifier analysis.

"Anatomy of a Circuit Design: A Function Generator" is set aside from the main text and appears between Chapters 3 and 4. It shows students how the material from the first three chapters can be used in designing a useful and interesting circuit.

Chapter 4 covers BJT characteristics, load-line analysis, large-signal models, biasing, small-signal equivalent circuit analysis, the common-emitter amplifier, the emitter follower, and use of the BJT as a switch in logic circuits.

Chapter 5 contains a similar treatment of FETs with the main emphasis on MOSFETs. If desired, the order of Chapters 5 and 6 can be reversed with little difficulty.

"Anatomy of a Circuit Design: A Multistage Amplifier" appears immediately after chapter 5 and illustrates how a multistage amplifier can be designed using what was learned from Chapters 4 and 5.

Chapter 6 treats digital logic circuits with very strong emphasis on CMOS. Basic logic circuit concepts, the resistor-pull-up NMOS inverter, the CMOS inverter, propagation delay, NOR and NAND gates, dynamic logic, and transmission gates are covered.

Differential and multistage integrated amplifiers including IC bias techniques are treated in Chapter 7.

Chapter 8 covers amplifier frequency response, including the Miller effect, the BJT hybrid-π model, and common amplifier configurations.

Chapter 9 examines feedback and oscillators. Sections 9.1 through 9.4 deal with types of feedback and their effects on gain and impedances. Then several design examples are given in Section 9.5. Sections 9.6 through 9.9 treat transient response, frequency response, and compensation of feedback amplifiers. Several examples of feedback amplifiers are discussed in Section 9.10. Finally, oscillator principles are discussed in Sections 9.11 and 9.12.

"Anatomy of a Circuit Design: A Cardiac Pacemaker" appears after Chapter 9 and shows an interesting application of many of the circuits and concepts discussed in the book.

Output stages and power supplies are presented in Chapter 10 including thermal considerations, power devices, Class A and B amplifiers, linear voltage regulators, and power-supply design.

Chapter 11 treats active filters, tuned circuits, impedance-matching networks, *LC* oscillators, and crystal oscillators.

Chapter 12 considers comparators, timer circuits and data converters, including the Schmitt trigger, multivibrator circuits, the 555 timer IC, digital-to-analog converters, and analog-to-digital converters.

Finally, "Anatomy of a Circuit Design: A Precision AC to DC Converter," illustrates another practical design using many of the concepts treated earlier in the book.

CHAPTER DEPENDENCY

The first five chapters form the foundation upon which the remainder of the book rests. The order of coverage of the remaining chapters is extremely flexible. Chapter 5 on MOSFETs can be covered before Chapter 4 on BJTs if desired.

ACKNOWLEDGMENTS

I wish to acknowledge my many friends at Michigan Technological University, ASEE, and elsewhere who gave help and encouragement in writing this text. I especially appreciate the enthusiastic support that I have received from my colleague Noel Schulz.

I am grateful to Dr. Orhan Soykan of Medtronic, Inc. for many helpful discussions and for contributing the section on cardiac pacemaker design that appears between Chapters 9 and 10.

A great deal of excellent advice has come from professors at other institutions who reviewed the manuscript in various stages. This advice has improved the final result very much, and I am grateful for their help. The reviewers for the first edition are: Robert Collin, Case Western University; W. T. Easter, North Carolina State University; John Pavlat, Iowa State University; Edward Yang, Columbia University; Ibrahim Abdel-Motaled, Northwestern University; Clifford Pollock, Cornell University; Victor Gerez, Montana State University; William Sayle II, Georgia Institute of Technology; Michael Reed, Carnegie Mellon University; D. B. Brumm, Michigan Technological University; Sunanda Mitra, Texas Tech University; and Elmer Grubbs, New Mexico Highlands University.

I would like to offer a special thanks to the reviewers who viewed drafts of this book, and provided their comments and insight. Our reviewers:

Gennady Gildenblat, Penn State;

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Art Davis, San Jose State University;

Albert H. Titus, Rochester Institue of Technology.

Finally, I thank my loving wife Judy for many good things too extensive to list.

Allan R. Hambley

Brief Contents

Contents

Introduction

1

The goal of this book is to give the reader a good understanding of the basic principles of digital and analog electronic circuits. The book emphasizes the application and design of integrated circuits; however, circuit design is most effective when it is carried out with a view toward the overall design process—as well as the particular system of which the circuit is to be a part. Therefore, this first chapter presents an overview of electronic systems, a general discussion of the steps in their design, and basic concepts related to digital systems and electronic amplifiers.

Electronic-circuit design is fun. You can earn a good living from it and impress many people to whom electronics seems like magic. Learning the material in this book is an important step toward a rewarding career as a designer of electronic systems.

1.1 ELECTRONIC SYSTEMS

Some electronic systems are familiar from everyday life. For example, we encounter radios, televisions, telephones, and computers on a daily basis. Other electronic systems are present in daily life, but are less obvious. Electronic systems control fuel mixture and ignition timing to maximize performance and minimize undesirable emissions from automobile engines. Electronics in weather satellites provide us with a continuous detailed picture of our planet.

Still other systems are even less familiar. For example, a system of satellites known as the **Global Positioning System** (GPS) has been developed by the United States to provide three-dimensional positional information for ships and aircraft anywhere on earth to an accuracy of several tens of meters. This is possible because signals emitted by several satellites can be received by the vehicle. By comparing the time of arrival of the signals and by using certain information contained in the received signals concerning the orbits of the satellites, the position of the vehicle can be determined. In addition, the received signals can be processed to set a local clock to an accuracy of about 100 ns.

Other electronic systems include the air-traffic control system, various radars, compact-disc recording equipment and players, two-way radios for police and marine communication, satellites that relay television and other signals from geosynchronous orbit, electronic instrumentation, manufacturing control systems, computerized monitors for patients in intensive care units, and navigation systems.

Electronic-System Block Diagrams

Functional blocks of electronic systems include amplifiers, filters, signal sources, wave-shaping circuits, digital logic functions, power supplies, and converters.

Electronic systems are composed of subsystems or functional blocks. These functional blocks can be categorized as **amplifiers**, **filters**, **signal sources**, **wave-shaping circuits**, **digital logic functions**, **digital memories, power supplies**, and **converters**. Briefly, we can say that amplifiers increase the power level of weak signals, filters separate desired signals from undesired signals and noise, signal sources generate waveforms such as sinusoids or square waves, wave-shaping circuits change one waveform into another (sinusoid to square wave, for example), digital logic functions process digital signals, memories store information in digital form, power supplies provide necessary dc power to the other functional blocks, and converters change signals from analog form to digital form or vice versa. Later in this chapter, we consider the external characteristics of amplifiers in some detail.

The block diagram of an AM radio is shown in Figure 1.1. Notice that there are three amplifiers and two filters. The local oscillator is an example of a signal source, and the peak detector is a special type of wave-shaping circuit. Digital circuits appear in the user interface (keypad and display) and in the frequency synthesizer. The digital circuits control channel selection and other functions, such as loudness. The complete system description would include detailed specifications for each block. For example, the gain, input impedance, and bandwidth of each amplifier would be given. (We will carefully define these terms later.) Each functional block in turn consists of a circuit composed of resistors, capacitors, inductors, transistors, integrated circuits, and other devices.

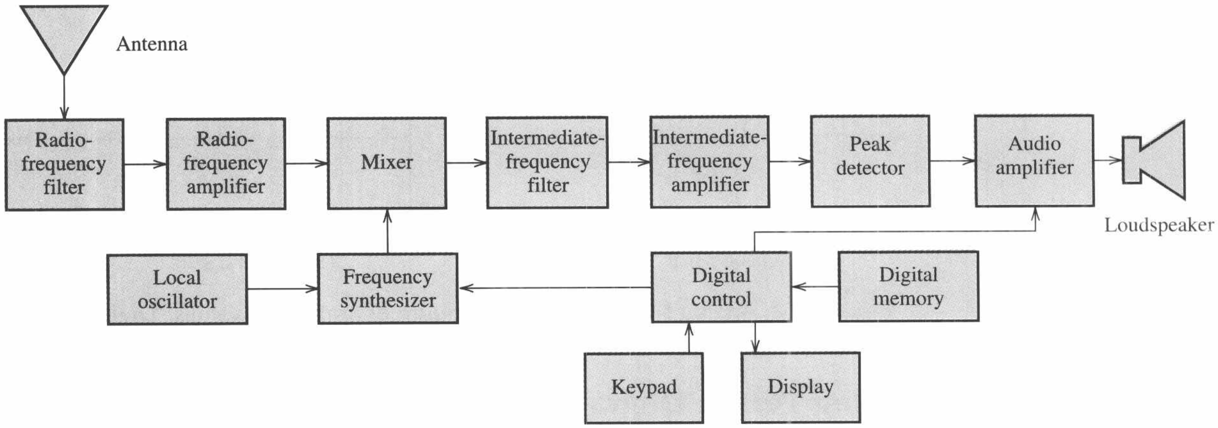

Figure 1.1 Block diagram of a simple electronic system: an AM radio.

The main goal of this book is to give you the basic skills needed to start from the external specifications of a block, such as an amplifier, and to design a practical circuit that meets the desired specifications. The selection of appropriate block diagrams for complex electronic systems is covered in other courses, such as control systems, computer architecture, digital signal processing, or communication systems.

The main goal of this book is to give you the basic skills needed to start from the external specifications of a block, such as an amplifier, and to design a practical circuit that meets the desired specifications.

Information Processing Versus Power Electronics

Many electronic systems fall into one or more of these categories: digital signal-processing systems, communication systems, medical electronics, instrumentation, control systems, and computer systems. A unifying aspect of these categories is that they all involve the collection and processing of information-bearing signals. Thus, the primary concern of many electronic systems is to extract, store, transport, or process the information in a signal.

Often, systems are also required to deliver substantial power to an output device. Certainly, this is true in an audio system, for which power must be delivered to loudspeakers to produce the desired sound level. In a control system for automatic positioning of a communication satellite, information extracted from various sources is used to control small rocket motors that maintain the satellite in its proper position and orientation. A cardiac pacemaker uses information extracted from the electrical signals produced by the heart to determine when to apply a stimulus in the form of a minute pulse of electricity to ensure proper pumping action. Although the output power of a pacemaker is very small, it is very important to consider the efficiency of its circuits to ensure a long life for the battery.

Some electronic systems are concerned mainly with the power content of signals, rather than information. For example, we might want a system to deliver ac electrical power (converted from dc supplied by batteries) to a computer, even when the ac line power fails.

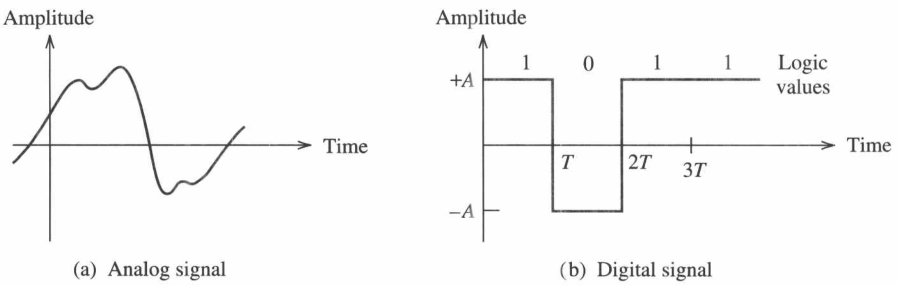

Figure 1.2 Analog signals take a continuum of amplitude values. Digital signals take a few discrete amplitudes.

Analog Versus Digital Systems

Information-bearing signals can be either analog or digital.

Information-bearing signals can be either **analog** or **digital**. An analog signal takes on a continuous range of amplitude values. The amplitude of a typical analog signal is plotted against time in Figure 1.2 (a). Notice that as time increases, the amplitude of the signal varies over a continuous range. On the other hand, a digital signal takes on a finite number of amplitudes. Often, digital signals are binary (i.e., there are only two possible amplitudes); however, more levels are sometimes useful. Frequently, digital signals change amplitude only at uniformly spaced points in time. An example of a digital signal is shown in Figure 1.2 (b).

The signals originally presented to the input of an electronic system by a **transducer** are usually in analog form. (A transducer is a device that converts energy to, or from, electrical form.) Examples of analog signals are sounds converted to electrical signals by a microphone, television signals, seismic vibrations, the output of a temperature transducer in a steam turbine, and so on. Other signals, such as the output of a computer keyboard, originate in digital form.

Conversion of Signals from Analog to Digital Form

Analog signals can be converted to digital form by a two-step process. First, the analog signal is sampled (i.e., measured) at periodic points in time. Then, a code word is assigned to represent the approximate value of each sample. Usually, the code words consist of binary symbols. This process is illustrated in Figure 1.3. Each sample value is represented by a 3-bit code word corresponding to the amplitude zone into which the sample falls. Thus, each sample value is converted into a code word, which in turn can be represented by a digital waveform, as shown in the figure. A circuit for the conversion of signals in this manner is called an **analog-to-digital converter** (ADC). Conversely, a **digital-to-analog converter** (DAC) converts digital signals back to analog form. (Later in the book, we discuss the design of both types of converters.)

The rate at which a signal must be sampled depends on the frequency content of the signal. (Signals can be considered to consist of sinusoidal components having various frequencies, amplitudes, and phases. Fourier analysis is a branch of mathematics that deals with this representation of signals. No doubt, you have had, or will have, other courses dealing with Fourier theory. We consider the frequency content of signals later in this chapter, but not on a rigorous mathematical basis.) If a signal contains no components

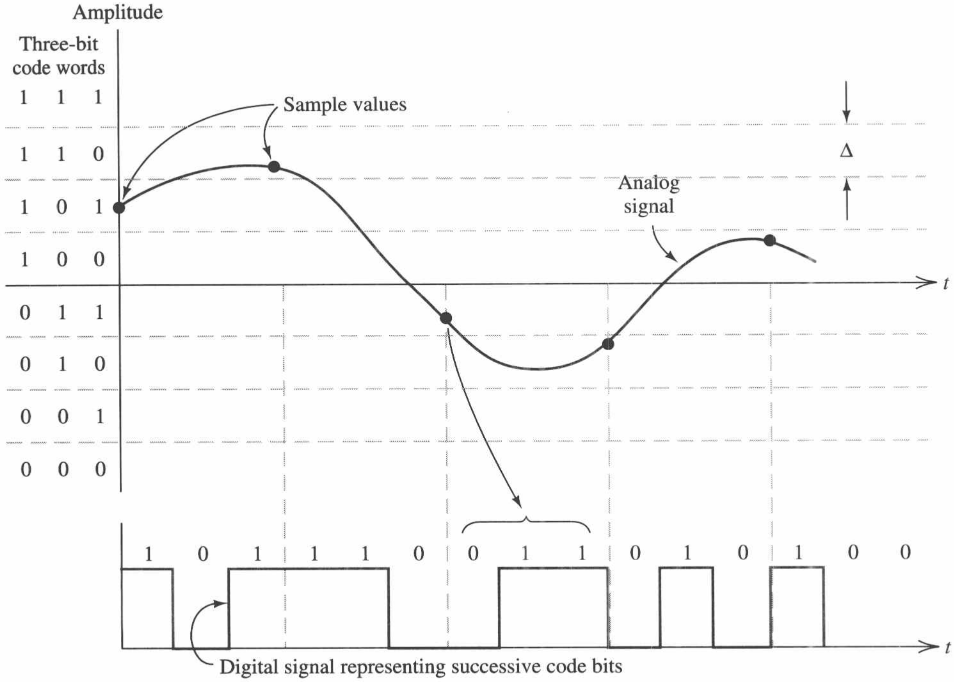

Figure 1.3 An analog signal is converted to an approximate digital equivalent by sampling. Each sample value is represented by a 3-bit code word. (Practical converters use longer code words.)

with frequencies higher than f_H, the signal can be exactly reconstructed from its samples, provided that the sampling rate is selected to be more than twice f_H. For example, audio signals have a highest frequency of about 15 kHz. Therefore, the minimum sampling rate that should be used for audio signals is 30 kHz. Practical considerations dictate a sampling frequency somewhat higher than the theoretical minimum. For instance, audio compact-disc technology converts audio signals to digital form with a sampling rate of 44.1 kHz. Naturally, it is desirable to use the lowest practical sampling rate to minimize the amount of data (in the form of code words) that must be stored or manipulated.

If a signal contains no components with frequencies higher than f_H, the signal can be exactly reconstructed from its samples, provided that the sampling rate is selected to be more than twice f_H.

Another consideration that is important in converting analog signals to digital form is the number of amplitude zones to be used. Exact signal amplitudes cannot be represented, because all amplitudes falling into a given zone have the same code word. Thus, when a DAC converts the code words to form the original analog waveform, it is possible to reconstruct only an approximation to the original signal—the reconstructed voltage is in the middle of each zone. This is illustrated in Figure 1.4. Consequently, some **quantization error** exists between the original signal and the reconstruction. This error can be reduced by using a larger number of zones, which requires a longer code word for each sample. The number N of amplitude zones is related to the number k of bits in a code word by

$$N = 2^k \tag{1.1}$$