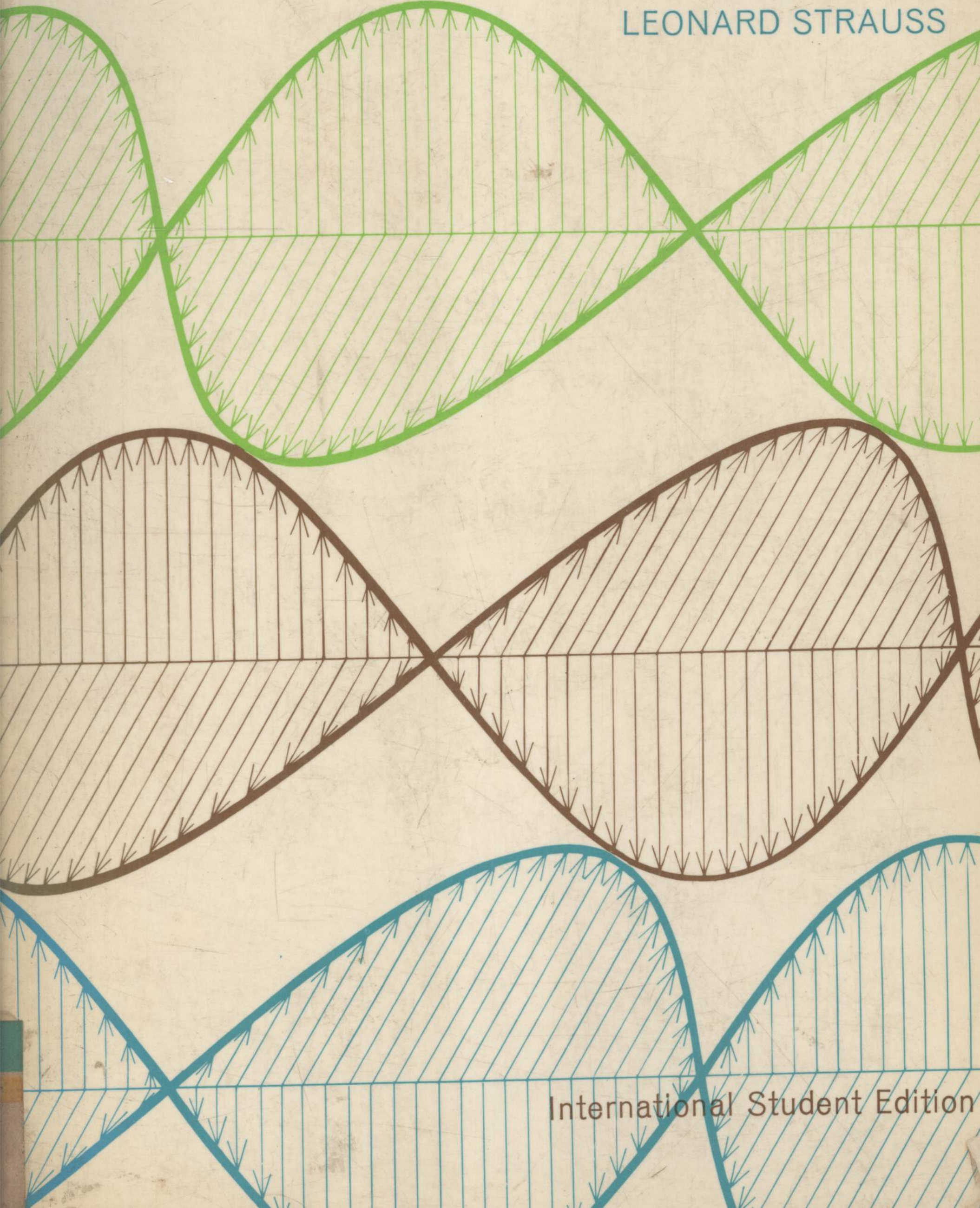
WAVE GENERATION AND SHAPING

Second Edition

LEONARD STRAUSS



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SECOND EDITION

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to Rosemary, Karen, and Neil

preface

In the decade since the publication of the first edition of this text, the coming of age of solid state technology has revolutionized active circuit design. Integrated circuits, which are diverse, plentiful, and economical, have replaced many of the standard discrete component circuits. The circuit designer has become more systems oriented, devoting a significant portion of his activity to the interconnection of digital and analog integrated circuit modules where whole circuit functions are treated as a single element. Much of standard instrumentation, equipment used for information processing, on-line computers, and generators of signals of specified geometries incorporate large numbers of integrated circuits.

Many circuits, especially those containing energy-storage elements, cannot be readily integrated. Prototypes and special-purpose circuits must still be fabricated out of discrete components. But even discrete component design has changed over the past decade. Because technological advances have reduced the cost of bipolar and field-effect transistors to the point where they are among the less expensive components, economics dictates the use of more and more transistors and fewer and fewer energy-storage elements. By combining discrete components with integrated modules, a new dimension in design can be obtained.

Since this book is written primarily as a text, its objective is to present a logical unified approach to the analysis of those circuits in which the nonlinearity of the active device is the significant factor. A developmental treatment is followed throughout as we focus on the essential features of practical wave generating, shaping, and logic circuits. Discrete bipolar transistors, FETs, digital, and analog integrated circuit building blocks are used interchangeably to support the contention that the basic mode of operation is independent of the type of active device employed.

To this end the text is arbitrarily divided into five parts: Models and Logic, Timing, Switching, Memory, and Oscillations. While it is, of course, impossible not to step across these bounds in discussing specific circuits, the examples in each section have been selected so that the basic ideas arise naturally from the discussion. In most cases, the analysis is sufficiently detailed so that the techniques may be applied to other existent, and not as yet existent, circuits.

The organization, which is described in some detail below, is a result of experimentation with class notes over several years. Because this work is primarily a text, designed for a senior or graduate course of one or two semesters, it is assumed that the reader is familiar with the transient analysis of linear networks and with simple bipolar transistor and FET models and circuits. However, since the viewpoint presented may be somewhat different from that previously encountered, some review material is incorporated in the body of the text at the point where it is first needed.

Part 1. Models and Logic. Since we are interested in the transient response of piecewise-linear models to various excitations, the first chapter presents approximation methods which can be employed for the rapid solution of linear circuits.

Chapter 2 introduces a grossly nonlinear element, the ideal diode. The model of an actual diode is then derived from the physics of the semiconductor junction and compared with the measured diode characteristic. Once the model is approximated by one of several different ordered series of line segments, linear algebraic equations may be written to define the behavior in each region. Most of the problems met in more complex circuits make their initial appearance when the diode is combined with an energy-storage element. Combinations of diodes and resistors can be used to represent, in piecewise manner, almost any arbitrary characteristic. For solution, the complex circuit is reduced to a sequence of linear networks and the complex problem reduces to finding the boundaries between the various regions (breakpoint analysis). Finally, an analysis of the dynamic behavior of the diode illustrates the internal time delays inherent in switching a semiconductor junction.

Because of the demands for faster and faster switching in the past decade, time scales have been improved by several orders of magnitude, from microseconds down to nanoseconds. Delays inherent in the operation of the active device have become the limiting factor. Since more sophisticated models are needed to explain the phenomena of interest, the engineer must keep returning to the physics of the solid state devices to develop these models.

Transistor models are derived from the semiconductor physics in Chapter 3. Both large signal limitations and small-signal models are treated as special cases of the two diode Ebers-Moll model. The dynamic response of a saturating inverter is used to define the rise, fall, and storage delay times typical of all switching circuits.

Chapter 4 combines diodes and transistors into basic logic circuits. Starting from simple diode AND and OR gates, the circuitry is made progressively more complex as the RTL, DTL, TTL, and ECL logics are developed. Integrated circuit geometries favoring specific logic classes illustrate the similarity between the diode AND gate and the TTL logic. Problems posed by the interconnection of logic arrays lead to the special output stages of the integrated circuit logics.

The junction field-effect transistor and the MOSFET are described in Chapter 5. It is indeed fortuitous that a voltage-controlled solid-state device does in fact exist. If it did not, the necessity of illustrating voltage controlled circuit behavior would either require the postulating of an ideal device or the inclusion of the essentially obsolete vacuum tube. The derived MOSFET model proves to be highly nonlinear. But combining one nonlinear active device with another connected as a load results in an extremely linear inverter stage where the gain is a function solely of the geometries of the MOSFETs. The geometry of MOSFET logic circuitry follows naturally. In solving for the dynamic response of the inverter pair, which we find is not of the exponential form, we introduce a new look at the solution of the transient response problem.

Part 2. Timing. The next two chapters deal with the linear sweep. Since the essential portion of any timing circuit is the exponential charging of an energy-storage element, the problem of analysis resolves itself into finding the time-constant, the initial, the steady-state, and the final sweep voltages.

In the simple voltage sweep of Chapter 6, an SCR is used as the switching element. This choice makes it possible to treat synchronization in a very straightforward manner.

Linearization of the sweep always involves some form of feedback. The aim is to approximate constant-current charging of the sweep capacitor. Calculation of the initial jumps, overshoots, and recovery exponentials from the several piecewise-linear circuit models lays the groundwork for the later analysis of the multivibrator and the blocking oscillator. Furthermore, the separate consideration of the recovery time and the switching problem leads to the construction of a sweep system.

Chapter 7 applies the same techniques of analysis to the current sweep.

Part 3. Switching. When a closed-loop system contains active elements, and when the loop gain is positive and greater than unity, we call it a switching circuit. If any timing networks are included in the transmission path, the circuit exhibits quasi-stable behavior. The same effect can be obtained by shunting a negative-resistance device with an energy-storage element.

Chapters 8 and 9 discuss a closed-loop regenerative switching circuit, the multivibrator. This circuit can be synthesized either with discrete components or by cross connecting two integrated logic circuits. We are mainly concerned with where and how to begin the analysis. A guess serves as the convenient starting point, and the circuit calculations are checked to see if they yield consistent results. If a contradiction arises, it simply indicates that the first guess was wrong. In the multivibrator, both transistors or FETs are active only during the switching interval. At all other times, one is cutoff or the other is saturated. Hence the exponential timing, which sustains the limiting, usually occurs within the cutoff zone, and recovery usually depends on the saturated transistor. After the appropriate models are drawn, the calculations involve finding the initial and switching points of the timing network.

Chapter 10 extends the concept of regenerative switching to the voltage comparator. External positive feedback converts any difference amplifier into a regenerative comparator exhibiting hysteresis.

Many devices exist whose driving-point volt-ampere characteristic exhibits a negative-resistance region. The most useful treatment of switching circuits containing these elements is from the viewpoint expressed in Chapter 11. Switching and timing are first treated with the aid of a postulated ideal device. Even though the waveshapes and trajectories obtained are approximately correct, the use of an ideal negative resistance leads directly to a stability criterion that may be inconsistent with the physical device. Since the reasons that the contradictory results arose are pointed out later, this chapter also illustrates the dangers inherent in over-idealizing a model.

The ideas presented in Chapter 11 may well be considered as some of the unifying concepts. These are presented rather late in the text so that the student may better appreciate the limitations as well as the advantages of this viewpoint. The negative-resistance treatment is useful for understanding the operation of all sweeps and switching circuits even where it is difficult to isolate the two terminals across which the negative resistance is developed. It is, however, a convenient design method only for those circuits which employ such special devices as the unijunction transistor, the *pnpn* transistor, and the tunnel diode.

Chapter 12 applies the methods developed in the earlier sections of the text to the blocking oscillator. Since extremely narrow pulses are generated, the rise and fall times become critical. Timing may depend on such diverse circuit factors as current buildup in a transistor and transformer core saturation. Care must be taken to select the significant one.

Part 4. Memory. Bistable multivibrators, formed by the interconnection of basic logic elements, serve as elementary memory cells. Chapter 13 shows how the *SR*, *JK*, and *D* type bistables are synthesized. Chains of these bistables can be interconnected to form shift registers, counters, and frequency dividers.

The structure of active memory arrays is left to Chapter 14. Here the subsystems of steering logic, storage, and read-write circuitry are examined in connection with specific memory configurations. Typical examples of short-time dynamic, long-time static, random access, and read only memories are examined in detail. This is where the MOSFET integrated circuit comes into its own, since from 1,000 to 4,000 active devices can be formed in an iterative structure on a single chip measuring less than $\frac{1}{10}$ in. on a side.

A hysteresis loop indicates memory and it therefore follows that magnetic and dielectric materials are ideally suited for information storage. Chapter 15 examines briefly the terminal characteristics of a core constructed out of ideal square-loop material. Furthermore, a clearly defined time is needed to saturate the core, and although not representable in a piecewise-linear manner, the driving-point impedance exhibits two distinct regions. This enables us to use either a core or a ferroelectric device as the timing element in a switching circuit.

Part 5. Oscillations. Although most of the circuits previously discussed depended for their timing on a single energy-storage element, at least two are necessary in order for the system to have a pair of complex conjugate poles located in the right half plane.

The sinusoidal oscillator is first treated as an almost linear feedback system (Chapter 16) which allows the separation of the frequency-, amplitude-, and gain-determining circuit elements. The role of each essential part of the oscillator is individually examined, with emphasis on minimizing the distortion and maximizing the stability. Since the signal produced is almost sinusoidal, the amplitude is readily found by plotting a system-describing function.

Chapter 17 returns to the negative-resistance viewpoint and describes the solution of a specific nonlinear differential equation. Here topological constructions, which supplement analytic methods, yield the waveshape and amplitude of oscillations. Hence the text ends by introducing a new topic and not by saying the last word on an old one.

While preparing this revision, I received a great deal of assistance from those of my colleagues who taught sections of courses for which this text was written. In stimulating technical discussions, I received the benefit of their ideas and thinking. They also corrected errors in the original class notes and they even contributed some of the problems. The typing and drafting assistance made available by the Polytechnic Institute of

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Leonard Strauss

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