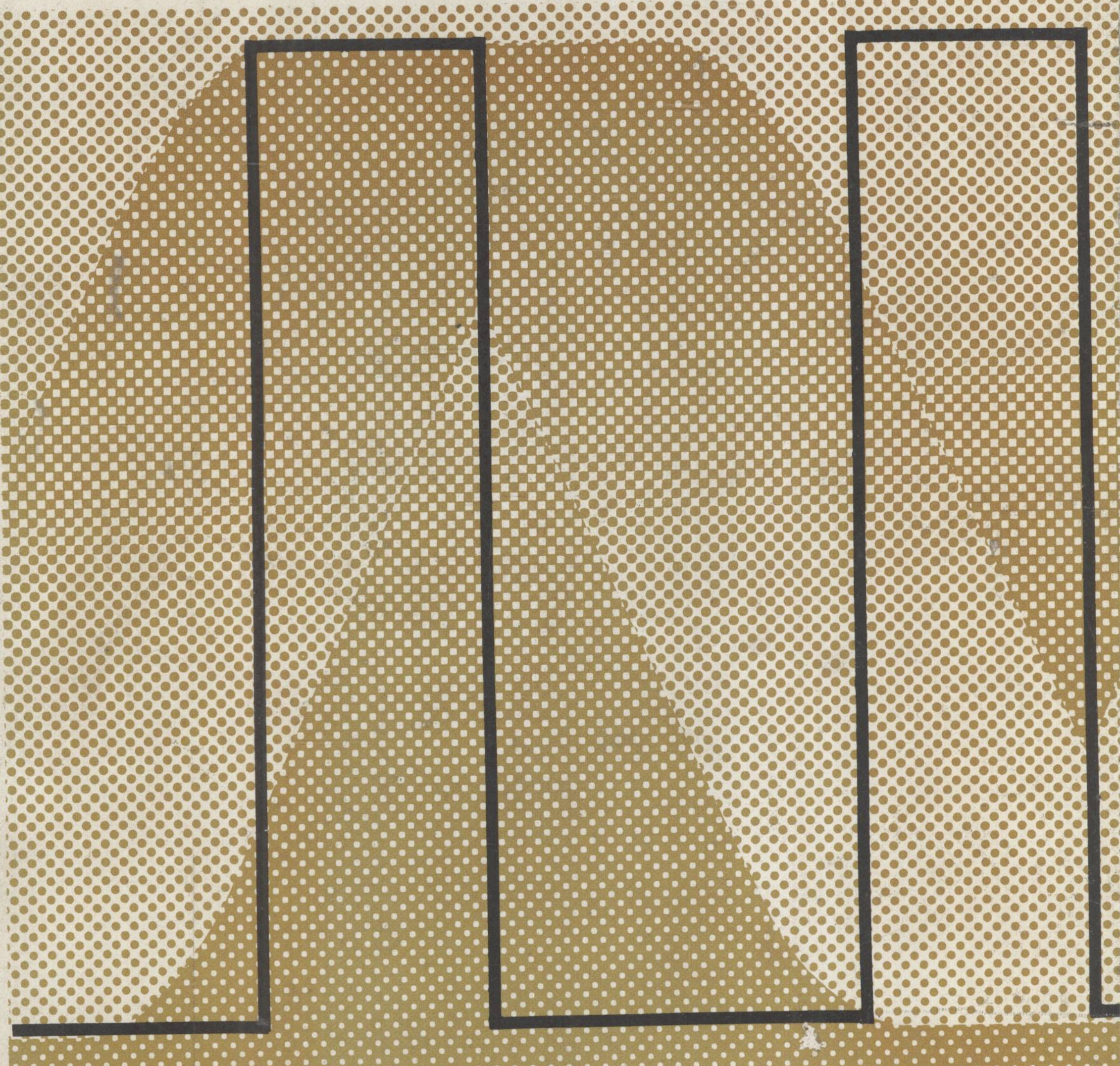
Analog and Digital Electronics for Scientific Application

Dennis Barnaal



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Breton Publishers
a division of Wadsworth, Inc.
North Scituate, Massachusetts

To Doris, Erik, Hans and Kari

ANALOG AND DIGITAL ELECTRONICS FOR SCIENTIFIC APPLICATION was prepared for publication by the following people: Shirley Pitcher, copy editor; Comprehensive Graphics, interior text designer; Wayne Williams, illustrator. Ellie Connolly supervised production. The book was set in Times Roman by Arabesque Composition; printing and binding on the Cameron Belt Press was by The Book Press. The sponsoring editor was Ed Francis.

The initial version of this book was prepared with the support of Luther College and National Science Foundation LOCI grant No. SER77-02795.

Breton Publishers
A Division of Wadsworth, Inc.

Library of Congress Cataloging in Publication Data

Barnaal, Dennis, 1936-
Analog and digital electronics for scientific application.

Also published separately under titles: Analog electronics for scientific application, and Digital and microprocessor electronics for scientific application.
Includes index.
1. Electronics. 2. Electronics—Scientific applications. 3. Digital electronics. 4. Microprocessors—Scientific applications. I. Title.
TK7816.B338 621.3815 82-1196
ISBN 0-534-01044-X AACR2

Printed in the United States of America
1 2 3 4 5 6 7 8 9 — 86 85 84 83 82

Preface

This book could be subtitled "A course in modern electronic techniques for students in physics, chemistry, computer science, engineering (other than electronic), biology, medicine, experimental psychology, geology. . . ." Such a title would illustrate the wide-ranging influence of electronic instruments and techniques in contemporary science. A laboratory in any area of science uses electronic instruments to study much of the phenomena under investigation. Indeed, electronics is pervasive throughout modern society.

People working in the areas listed above need an acquaintance with electronics for a number of reasons: to make proper use of instruments; to understand instruments including new instruments becoming available; to conceive of new possibilities and techniques and convey them to designers; and, on occasion, to save time and keep the operations going by fixing the instrument or building it oneself!

Because of these needs electronics courses have been taught in physics departments for many years. However, they have typically been "scaled-down electrical engineering courses" that emphasize the design of various amplifier types from transistors. This approach is not well suited to the needs of scientists, for there is little time to consider the *overall design of instrument systems.* For most laboratory applications we need not concern ourselves with complex amplifier design, particularly now with the sophisticated linear and digital integrated circuits available. Students in biology, chemistry, and medicine in particular can solve almost all amplifier problems with that powerful function block, the *operational amplifier.*

Therefore this book relegates discrete active devices to the last chapter of the analog electronics section. The design of function blocks around integrated-circuit devices and their implementation into instrumentation for representative tasks in science and medicine are emphasized. Application of the various electronic techniques in the laboratory are frequently outlined; in general I have tried to avoid simply presenting a catalog of circuit types.

Approximately the first half of this book deals with analog electronics, while the second half deals with digital and microprocessor electronics. A comment on analog versus digital is in order here. In the era of the 1980s, almost everyone has an idea of the difference between the two. People are familiar, for example, with the widely used digital watch that now often replaces the "analog watch" on wrists. The term *digital* implies the use of discrete numbers and electronic circuits that are just "on" or "off" like a switch. The term *analog* implies the use of a needle (such as a watch hand) along the range of a scale and electronic circuits wherein currents and voltages may be any of a range of values.

A good understanding of Ohm's Law and dc circuits, as well as basic ac circuits, remains important in electronics. Chapter A1 reviews and occasionally extends these basic areas for the student. Chapter A2 describes some important features of various kinds of measuring equipment and instruments used in electronics and the laboratory. Electronics is useful because of its contact with the physical world through appropriate transducers, and Chapter A3 introduces a selection of these devices. After diodes and basic power supplies are discussed in Chapter A4, some general features of amplifiers and amplifier use are examined in Chapter A5. Then Chapters A6 and A7 represent the kernel of the analog section as they survey the uses of linear integrated circuits, especially the operational amplifier. Finally, Chapter A8 presents various transistor types and a basic understanding of their characteristics and use.

For a long time scientific electronics courses included a modest section dealing with pulses and counting circuits. However, since digital logic integrated circuits became available in 1965, the performance and low cost of these devices have promoted digital techniques to equal importance with analog electronics as a tool for scientists. For example, the digital voltmeter and the microcomputer are now commonplace in the laboratory.

The first *minicomputer*—the PDP–8/E from Digital Equipment Corporation—was introduced in about 1965 for approximately $20,000. This price permitted the minicomputer to become an element of laboratory instrumentation. However, the computer revolution continued as Intel Corporation invented the first 4-bit *microprocessor* in 1971. Within a few years more sophisticated 8-bit and 16-bit microprocessors were developed and incorporated into *microcomputers* that rival the minicomputer in capability. Furthermore, microprocessor chips can be purchased for less than $8 and make possible "intelligent" scientific equipment as well as new digital approaches to data acquisition and analysis.

Microprocessor design has replaced detailed logic design in many of the more complex digital electronics applications. However, a study of digital logic is still very useful for several reasons: to design digital logic elements into various types of electronic instrumentation; to understand and occasionally repair existing digital instrumentation; and to interface microprocessors or minicomputers to laboratory equipment and industrial processes. Therefore the first half of the digital portion of this book is devoted to digital logic concepts and techniques.

Chapters D1 and D2 present digital logic elements and circuits, while Chapters D3 and D4 introduce flip-flops and counting circuits. The level and selection of topics are designed especially for the scientist and general engineer; advanced design techniques typical of a text intended for a professional digital designer are avoided. The digital logic chapters culminate with Chapter D6, which discusses how digital instruments can be developed from these concepts.

The last half of the digital section examines the characteristics and application of an important microprocessor, the 6502. In this concise course, no attempt is made to survey the many types of microprocessors available. Because it is often necessary to program a microprocessor in its *machine language* for high-speed *real-time* laboratory applications, a basic instruction set and essential machine language programming techniques for the 6502 microprocessor are developed in the microprocessor chapters. It is *not* assumed that the reader has studied machine language programming previously, although previous work with computer programming in a higher-level language such as BASIC is helpful. The goal of the four microprocessor chapters is to provide the scientist with a training in microprocessors sufficient to develop and apply microprocessor-based laboratory instrumentation.

As background for the course, the book assumes only that the student has studied electricity in the context of a noncalculus college physics course. However, the first chapter provides a reasonably self-contained review of these topics, and the preliminary version of this book has been used in a general nonprerequisite course at one institution. Higher mathematics has been completely avoided; almost all derivations require only Ohm's Law and some algebra.

At Luther College, the analog and digital electronics sections of this book are taught as a pair of 2-credit courses; these are generally elected by physics majors and pre-engineering students as a 4-credit semester-long course (3 lectures and one 3-hour laboratory each week) in the first semester of their second year. The study of electronics early in the curriculum of physical science permits this important tool to be realistically exploited throughout later laboratory work. Nonphysics majors typically elect one or both of the minicourses during their third or fourth year in college. The analog and digital sections of this book are available as separate paperback books to serve the latter students.

Laboratory work remains crucial to the art of using electronics. Merely reading about it is not enough; a certain intuition needs to be developed through *doing*. To assist the student in developing this intuition, electronics diagrams in this book often include values for components; furthermore, "nitty-gritty" problems and practice of real-world electronics as used in the laboratory are often mentioned. A laboratory manual with a selection of analog, digital, and microprocessor experiments to complement this book is available. The experiments utilize inexpensive breadboard techniques for analog and digital experimentation, together with commonly available electronic instruments. The KIM and SYM microcomputer boards are used for the microprocessor experimentation and are used in the microprocessor examples in this book.

Finally, it should be mentioned that a number of my colleagues reviewed the manuscript during the various stages of its development. Thanks for their helpful comments and suggestions are extended to Charles Duke, Grinnell College; Mark J. Engebretson, Augsburg College; Roy Knispel, University of Wisconsin; and Thomas I. Moran, University of Connecticut. A special word of thanks goes to Ed Francis of Breton Publishers who inspired me to develop my original work into a textbook suited to a broad, national audience. And Ellie Connolly of the Breton production staff is to be commended for her many contributions to the final product.

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Contents

DIGITAL AND MICROPROCESSOR ELECTRONICS FOR SCIENTIFIC APPLICATION

CHAPTER A1

Passive Components and Networks

The first chapter deals with elements of electronics that do not "amplify"; that is, they do not cause an increase in the power level of the signal. Much of the material is at least touched upon in a first-year physics course (considered a prerequisite to this book). Although the presentation is reasonably self-contained, the first chapter functions primarily as a review. Nonamplifying elements, however, are the foundation of electronics, and any rusty memories must be reoiled. Further, working with electronics is applying Ohm's Law again and again; therefore, the student must understand basic circuits very well.

In the course of the chapter we review electrical concepts such as charge, current, resistance, voltage, and electrical power. We consider how to analyze the behavior of dc circuits and simple ac circuits. The important passive elements are reviewed; these include the resistor, potentiometer, battery, capacitor, inductor, and transformer. However, we do discuss important characteristics of the real components used in electronics, and this may not be review material. Also, the emphasis with respect to ac circuits is on frequency filter circuits. Finally, a remarkable property of electrical circuits called Thevenin's Theorem is discussed. This theorem is the basis of an approach to electronics that is emphasized in this book—that is, the black box model of amplifiers and system components. Although the contents of the boxes may change over the years, this approach promises general and quite timeless utility.

Summary of Basic Concepts

Electricity begins with the Coulomb Law for the force F between point electrical charges Q_1 and Q_2 that are a distance r apart. In MKS or SI units it is

$$F = k\left(\frac{Q_1 Q_2}{r^2}\right) \qquad \text{(A1–1)}$$

where $k = 8.987 \times 10^9 (\simeq 9 \times 10^9)\,\mathrm{Nm^2/C^2} = 1/(4\pi\epsilon_0)$

The unit of charge is the *coulomb*, which is defined through current in the MKS system. We have the familiar story that unlike charges attract and like charges repel. We imagine that a charge experiences a force because of the electrical field at that point due to other charges. If F is the force on a charge Q, then the electric field E at that point is

$$\vec{E} = \frac{\vec{F}}{Q} \qquad \text{(A1–2)}$$

Combining Equations A1–1 and A1–2 quickly shows that the magnitude of electric field due to an isolated point charge Q is

$$E = \frac{kQ}{r^2} \qquad \text{(A1–3)}$$

where r is the distance from the charge. The total electric field from a group of charges is the vector sum of individual contributions given by Equation A1–3.

If one moves a charge Q between two points A and B in an electric field, *work* W is generally done (a force is exerted through a distance). We speak of the *potential difference* or the *voltage difference* V_{AB} between two points; that is,

$$V_{AB} = \frac{W}{Q} \qquad \text{(A1–4)}$$

Thus the voltage between two points is the *"work per unit charge"* to move the charge between the two points, and the units are joules/coulomb ≡ volts in the MKS system. Since these are the "practical units" of the electrician, MKS units have become dominant in electronics and, indeed, throughout science. One of the remarkable features of electric fields is that the work done in moving a charge between two points is independent of the path followed. This permits us to speak of a *conservative field* and to use the term *potential.* Kirchhoff's second law follows directly from this fact, as we note shortly.

Charges in motion constitute electric current. The net charge passing through a surface per second is the current in amperes. If ΔQ is the net charge that flows in a time Δt, then the current I is

$$I = \frac{\Delta Q}{\Delta t} \qquad \textbf{(A1–5)}$$

It follows that 1 ampere = 1 coulomb/second.

The direction of conventional current flow is the direction that positive charges move (or at least would move if they were there). Negative charge moving in the opposite direction is counted as equal to positive current moving in the conventional direction. Thus, ions of opposite sign in an electrolyte solution move in opposite directions, but these currents add when calculating net current.

Review of dc Circuits

The first section of our review covers circuits and circuit elements for the case when the current is nearly constant and in one direction only—that is, the *direct current* or *dc* case.

Ohm's Law

If a voltage difference exists between two points on a length of wire or other material, the difference is due to the existence of an electric field between the two points. Any charges—that is, *charge carriers*—that are free to move in the material will do so because of the push of the electric field. The charges move at a *drift velocity* that is limited by frictional effects in the material, and a certain current results. The current is proportional to the push of the electric field that in turn is proportional to the voltage difference between the two points. On the other hand, it is inversely proportional to the frictional effects, or *resistance R*, to current flow between the two points. We write this as Ohm's Law:

$$I = \frac{V}{R} \quad \text{or} \quad V = IR \qquad \textbf{(A1–6)}$$

The unit of resistance is the *ohm* and Equation A1–6 shows 1 ohm = 1 volt/ampere.

The resistance of a length of wire is proportional to its length L but inversely proportional to its cross-sectional area A. We have

$$R = \frac{\rho L}{A} \qquad \textbf{(A1–7)}$$

where the proportionality constant ρ is called the *resistivity* of the material used for the wire. Table A1–1 gives resistivities for several metals, alloys, and insulators at room temperature.

TABLE A1–1. *Some Resistivities*

Material	*Resistivity (ρ) in 10^{-8} ohms × meters*
Silver	1.5
Copper	1.7
Aluminum	2.6
Manganin	44.0
Constantan	50.0
Nichrome	100.0
Carbon	350.0
Silicon (pure)	625.0
Glass	10^{20}

Batteries

Batteries serve as electrical elements that by chemical action maintain a potential difference (voltage) between two terminals whether a current is flowing or not. A single cell consists of two electrodes made from different materials that are inserted in some electrolyte. The potential or *emf* of the cell is determined by the composition of the electrodes and the electrolyte concentrations, not by the physical size of the cell. Strictly speaking, batteries are cells that are connected in series to increase the voltage; however, the term is often used for single cells as well. Figure A1–1 shows the conventional circuit symbols for a cell and a battery.

Batteries have regained popularity in electronics because of the low power requirements of contemporary solid-state circuits. They are necessary for equipment used in remote places and useful when equipment must be isolated from power line (wall socket) noise. It is desirable for the circuit designer and the user to have a basic knowledge of different cell characteristics.

The *lead-acid storage battery* is the common car battery in the United States and has been in use for many years. It has an emf of 2.06 V to 2.14 V when charged, requires a liquid (acid) electrolyte, is heavy because of the lead, and is capable of high currents (up to hundreds of amperes). It is rechargeable by reversing the current through the battery and thus is reusable for a few years. A sealed form is now available.

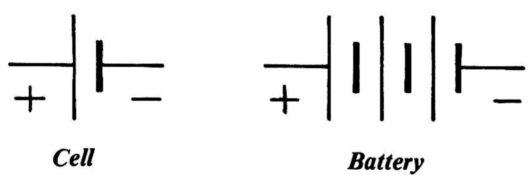

FIGURE A1–1. *Conventional Circuit Symbols for a Cell and a Battery*

The *carbon-zinc battery* is the familiar flashlight battery of many years use. It is called a *dry cell* because of the paste electrolyte used and has a fresh emf of about 1.55 V. It is inexpensive but has poor performance at low temperatures and a shelf life only of a year or so; that is, even if unused (or left on the shelf), it becomes useless after a period of time because of the internal discharge that takes place. The battery can be only partially recharged over a period equaling the shelf life.

The *alkaline-manganese battery* is another paste electrolyte cell with an emf of about 1.5 V. It has a higher current capability and longer shelf life than the carbon-zinc, but at approximately four times the price. It is not rechargeable.

The *nickel-cadmium battery* is a rechargeable battery that has been used in Europe for many years but is perhaps twice as expensive as the lead-acid type. It uses a liquid electrolyte, but is available in sealed form in smaller sizes (for example, for use in calculators). It is capable of high discharge and charge rates and has a long service life. The cell emf varies from 1.4 V at full charge to about 1.25 V for most of the discharge period.

The *mercury battery* is popular in scientific instruments because its voltage remains very constant at 1.35 V over the discharge period of the battery. It uses a paste electrolyte, but is considerably more expensive than other paste types and does not perform well at low temperatures. See the forms of discharge curves for several battery types in Figure A1–2.

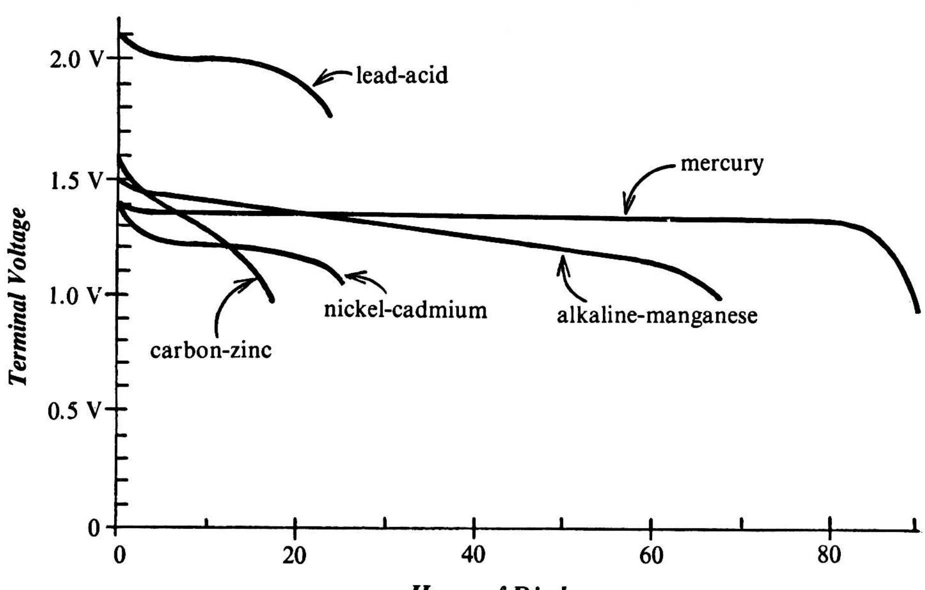

FIGURE A1–2. *Discharge Curves for Several Battery Types*

For all battery types it is important to use a battery that is physically large enough to handle the current drain. Large plate area implies a lower internal resistance and less heat dissipated in the battery, as well as a smaller drop in terminal voltage. Batteries are rated in *ampere-hours,* or in *milliampere-hours.* This rating is simply the product of current drain times the discharge period that we may expect from the battery, and is basically a unit of energy. Eveready (Union Carbide) has a substantial handbook listing properties of their large line of dry cells.

Power in Electrical Circuits

The *voltage* of a battery is the work per unit charge to move the charge from one terminal to the other. If positive charge Q moves from the positive terminal to the negative terminal, the battery performs work W equal to VQ. *Power* P is the time rate of doing work. Dividing by the time involved quickly gives (for steady current)

$$P = \frac{W}{t} = V\left(\frac{Q}{t}\right) = VI \qquad P = VI \qquad \textbf{(A1–8a)}$$

as the power delivered when a current flows between a voltage difference V. If the voltage appears across a resistance R, Ohm's Law gives two alternate ways to compute the power (in the form of heat dissipated in the resistor):

$$P = I^2 R \qquad P = \frac{V^2}{R} \qquad \textbf{(A1–8b)}$$

When the current is in amperes, the voltage in volts, and resistance in ohms, the resulting power is in *watts.*

Resistors

Electronics makes regular use of circuit elements with definite resistance, called *resistors.* Various types of resistors are made to fit the needs of low cost, small size, high power consumption, high accuracy, low-temperature effects, and so on. It is not possible to meet all of these requirements with one type.

The basic *fixed resistor* (or simply *resistor*) is a large length of wire wound as a coil on a ceramic tube. Material of high resistivity is chosen so that the length is not outlandish. Further, temperature has a small effect on the resistance, and nichrome or manganin wire are often used to meet these two requirements. The circuit symbol for a resistor is a zig-zag line suggested by the side view of a coil of wire (see Figure A1–3).