

Electronic Instrumentation

JOHN A. ALLOCCA

ALLEN STUART

73.865
A441

Electronic Instrumentation

JOHN A. ALLOCCA

ALLEN STUART



8550229
Reston Publishing Company, Inc.
A Prentice-Hall Company
Reston, Virginia

8550229

To my children, Jennifer and Jerry;
my mother and father, Dorothy and
Frank; my brother, Frank; and my friend,
Jon-Ellyn.

John A. Allocca

To Ida and Max, Janice, Bernice, and
Manuel.

Allen Stuart

DSS1/E1
Library of Congress Cataloging in Publication Data

Allocca, John A.

Electronic instrumentation.

Includes bibliographies.

1. Electronic instruments. 2. Medical electronics.

I. Stuart, Allen. II. Title.

TK7878.4.A45 1983

621.381

82-25020

ISBN 0-8359-1633-2

Editorial/production supervision and interior design
by Barbara J. Gardetto

© 1983 by

Reston Publishing Company, Inc.

A Prentice-Hall Company

Reston, Virginia 22090

*All rights reserved. No part of this book may be
reproduced in any way, or by any means, without
permission in writing from the publisher.*

10 9 8 7 6 5 4 3 2 1

Printed in the United States of America

8880662

Preface

The first nine chapters of this first edition of *Electronic Instrumentation* have been written as a text for a two- or three-year electrical engineering college curriculum. The next six chapters are intended for students taking a course in computer science or engineering. The textbook can also be adapted for technical institutes or as an elective in a community college. Chapter 16 introduces the student to *bioelectronic* instrumentation. The goal of the writers is to introduce their audience to the latest in instrumentation in industry and medical applications. The text also serves as a handbook for practicing engineers and technologists.

Chapter 1 covers the instruments for analog and digital circuit elements. Chapter 2 stresses instrumentation transducers. Chapter 3 introduces the reader to data-acquisition systems. Chapters 4 through 6 cover analog signal conversion to a digitized waveform and rerouting of that signal to an analog or digital readout. Chapter 7 stresses electronic instrumentation waveform generation and spectrum analyzers and Chapter 8 emphasizes the latest in oscilloscopes. Chapter 9 covers analog and digital readout devices and Chapters 10 through 15, computer-aided systems, computer-based systems including sensors, electronic counters, data-processing systems, and microprocessors and microcomputers. Chapter 16 introduces the student to specialized health-care technology. Each chapter includes review questions and references.

The authors wish to thank the Keithley Instrument Co., Datel-Intersil Inc., Global Specialities Corp., Sencore, International Business Machines Corp., Hewlett-Packard Co., and the many other manufacturers who have made significant contributions to this text. Without their help, this book would not have been possible.

The authors finally acknowledge Mr. David Dusthimer, Electronic Technology Editor, and Mrs. Linda MacInnes of Reston Publishing Co. for their support of this project.

John A. Allocca
Allen Stuart

Contents

Preface ix

1

ELECTRONIC INSTRUMENTS USED TO MEASURE ANALOG AND DIGITAL CIRCUIT ELEMENTS 1

- 1.1 Introduction 1
- 1.2 The Digital Multimeter 3
- 1.3 Microprocessors and the Digital Multimeter 8
- 1.4 The Bench DMM 10
- 1.5 The System DMM 11
- 1.6 Electrometers 12
- 1.7 High-Resistance Electrometer Measurements 19
- 1.8 Voltage Measurements from High-Resistance Sources 21
- 1.9 Other Electrometer Uses 22
- 1.10 Nanovoltmeters 22
- 1.11 Experimental Application of the Digital Multimeter 25
- 1.12 Other Important Electronic Instruments 29
- 1.13 Review Questions 35
- 1.14 References 35

2

TRANSDUCERS ASSOCIATED WITH ELECTRONIC INSTRUMENTATION 37

- 2.1 Introduction 37
- 2.2 Strain Gage Transducer as a Displacement Device 44
- 2.3 Applications of Blood-Pressure Transducers 47
- 2.4 Strain Gage Calibration Technique 49
- 2.5 Capacitance as a Displacement Transducer 57
- 2.6 Linear Variable Transformer Transducer as a Displacement Device 64
- 2.7 Piezoelectric Transducer as a Displacement Device 65
- 2.8 Potentiometer Transducer as a Displacement Device 67
- 2.9 Resistance Thermometer as a Temperature Device 67
- 2.10 Thermistor as a Temperature Device 71
- 2.11 Thermocouple as a Temperature Device 72
- 2.12 Photoemissive Tube as a Light Device 74
- 2.13 Photovoltaic Cells as Light Devices 76
- 2.14 Photoconductive Cell as a Light Device 82
- 2.15 Lasers 85
- 2.16 Fiber Optic Transducers 85
- 2.17 Review Questions 86
- 2.18 References 86

3

DATA-ACQUISITION SYSTEMS 88

- 3.1 Introduction 88
- 3.2 Coding for Data Converters 92
- 3.3 Operational and Instrumentation Amplifiers 96
- 3.4 Filters 100
- 3.5 Settling Time 101
- 3.6 Analog Multiplexer Operation 104
- 3.7 Operation of Sample-Hold Circuits 108
- 3.8 Review Questions 112
- 3.9 References 113

4

ANALOG-TO-DIGITAL CONVERTERS 114

- 4.1 Introduction 114
- 4.2 A/D Converter Terminology and Parameters 115
- 4.3 General Applications of A/D Converters 121
- 4.4 Multiplexers (MUX) 122
- 4.5 Sample-Hold and Track-Hold Modules 123
- 4.6 Video A/D Converters 125
- 4.7 Video Frequency Multiplexer 127
- 4.8 Synchro and Resolver Converters 132
- 4.9 Synchro-to-Digital and Resolver-to-Digital Converters 139

- 4.10 Specialized Applications of the A/D Converter 144
- 4.11 Review Questions 154
- 4.12 References 155

5

DIGITAL INSTRUMENTATION SYSTEMS 156

- 5.1 Introduction 156
- 5.2 IC Logic Devices 156
- 5.3 Logic Probes 161
- 5.4 Logic Monitors 170
- 5.5 Digital Pulser 175
- 5.6 Logic Analyzers 178
- 5.7 Digital IC Test System 179
- 5.8 Digital Multimeter Operation Theory 182
- 5.9 Digital Panel Meters 191
- 5.10 Data-Acquisition Application to Computers 194
- 5.11 Review Questions 197
- 5.12 References 197

6

DIGITAL-TO-ANALOG CONVERTERS 198

- 6.1 Introduction 198
- 6.2 Digital Converter Codes 198
- 6.3 Translation Between Codes 201
- 6.4 Transfer Characteristics and Accuracy 204
- 6.5 Digital-to-Analog General Concepts 206
- 6.6 Digital-to-Analog Systems 210
- 6.7 Multiplying D/A Converters and Applications 211
- 6.8 Video D/A Converters 213
- 6.9 Digital-to-Synchro and Digital-to-Resolver Converters 214
- 6.10 Specialized Applications of the D/A Converter 218
- 6.11 Review Questions 227
- 6.12 References 228

7

ELECTRONIC INSTRUMENTATION WAVEFORM GENERATION 229

- 7.1 Introduction 229
- 7.2 The Function Generator 230
- 7.3 Microprocessor-Based Fully Programmable Sweep Oscillator 243
- 7.4 Pulse Generators 244
- 7.5 General Specialized Applications for Pulse Generators 257
- 7.6 Basic Signal Analyzer Concepts 259
- 7.7 The Spectrum Analyzer 260

- 7.8 Review Questions 274
- 7.9 References 274

8

OSCILLOSCOPES 276

- 8.1 Introduction 276
- 8.2 Elements and Terminology of Oscilloscopes 277
- 8.3 Cathode-Ray Tube Reflection Fundamentals 278
- 8.4 Cathode-Ray Tube Picture Drawing Fundamentals 281
- 8.5 The Dual-Trace Oscilloscope 287
- 8.6 Introduction to the Digital Oscilloscope 291
- 8.7 Review Questions 307
- 8.8 References 308

9

ANALOG AND DIGITAL READOUT DEVICES 309

- 9.1 Introduction 309
- 9.2 Analog and Digital Readout Recorders 313
- 9.3 Light-Emitting Diodes 326
- 9.4 Special Digital Readout Applications 334
- 9.5 Review Questions 349
- 9.6 References 349

10

INPUT-OUTPUT DEVICES 350

- 10.1 Introduction 350
- 10.2 Electronic Instrumentation System 351
- 10.3 Computer Input-Output Devices: Examples 351
- 10.4 Digital Computer 352
- 10.5 Block Diagrams of Computer Input-Output Devices 353
- 10.6 Different Instruments with Input-Output (Generalized) 355
- 10.7 Block Diagram for Generalized Input-Output Systems, Including the Concept of Modem 358
- 10.8 Illustrative Problems for Input-Output Devices 361
- 10.9 Input-Output Devices in Hospitals 374
- 10.10 Review Questions 376
- 10.11 References 377

11

COMPUTER-AIDED INSTRUMENTATION SYSTEMS 378

- 11.1 Introduction 378
- 11.2 Computer-Aided Design and Computer-Aided Manufacturing (CAD/CAM) in Electronics 379

- 11.3 An Economic Necessity 381
- 11.4 CAD/CAM in PCB Manufacturing 383
- 11.5 Applications of Small Computers in Laboratory Research 397
- 11.6 Computer-Assisted Management of Occupational Health Programs 401
- 11.7 Computer-Assisted Cardiac Laboratory 402
- 11.8 Computer-Assisted Preventive Maintenance Program 403
- 11.9 Automatic Test System for the Bioelectric Pacemaker 404
- 11.10 Review Questions 405
- 11.11 References 406

12

COMPUTER-BASED SYSTEMS, INCLUDING TRANSDUCERS 407

- 12.1 Introduction 407
- 12.2 Data-Acquisition Instruments for Transducer Measurements 408
- 12.3 Thermistor Data Logger Instrumentation 412
- 12.4 Data Acquisition and Conversion Systems for Linear Variable Differential Transformers 414
- 12.5 A/D Techniques for High-Performance Data-Acquisition Systems 420
- 12.6 A Practical High-Speed Data-Acquisition System 428
- 12.7 The SineTrac Concept 432
- 12.8 Review Questions 438
- 12.9 References 439

13

ELECTRONIC COUNTERS 440

- 13.1 Introduction 440
- 13.2 The 100-MHz Frequency Counter 441
- 13.3 The Universal Counter-timer 453
- 13.4 The Frequency Standard 463
- 13.5 Review Questions 471
- 13.6 References 471

14

DATA-PROCESSING SYSTEMS 473

- 14.1 Introduction 473
- 14.2 Data Representation 484
- 14.3 Storage Devices 492
- 14.4 Central Processing Unit (CPU) 497
- 14.5 Data-Processing Input-Output Devices 504
- 14.6 Teleprocessing 512
- 14.7 Review Questions 516
- 14.8 References 517

15

MICROPROCESSORS AND MICROCOMPUTERS 518

- 15.1 Introduction 518
- 15.2 Terms Used for Understanding Microprocessors and Integrated Circuits 522
- 15.3 Binary Digit Concepts 524
- 15.4 Arithmetic and Logical Functions 529
- 15.5 Mnemonics 542
- 15.6 The Intel 8-, 16-, and 32-Bit Microprocessor 546
- 15.7 Application of the Microprocessor 558
- 15.8 Emulation for Microprocessors 564
- 15.9 Microprocessor-Based Testing Problems 568
- 15.10 IEEE-488 Bus Interface System and Computer-Automated Measurement and Control Interface (CAMAC) 572
- 15.11 Review Questions 586
- 15.12 References 587

16

SPECIALIZED BIOELECTRONIC INSTRUMENTATION 589

- 16.1 Introduction 589
- 16.2 Electrical Potentials Generated Within the Heart (Generation of the Electrocardiogram Waveform) 589
- 16.3 Measuring Bioelectric Potentials 592
- 16.4 Defibrillators 592
- 16.5 Blood-Pressure Transducers 594
- 16.6 Swan-Ganz Catheter 597
- 16.7 Electrode Contact 598
- 16.8 Electrical Safety of Medical Equipment 601
- 16.9 Cardiac-Care Systems 604
- 16.10 A New Electrocardiogram Using Microprocessors and a Microcomputer 612
- 16.11 Review Questions 615
- 16.12 References 616
- 16.13 Magazines and Periodicals Related to Medical Safety 616

Appendixes 619

Index 640

1

Electronic Instruments Used to Measure Analog and Digital Circuit Elements

1.1 INTRODUCTION

In any electronic circuit, we can monitor voltage, current, or impedance. We can use a probe and attach it to points of an electronic circuit. The voltage and current signal can be read on an analog or digital multimeter. Today, we use the digital multimeter because considerable progress has been made in the field of digital technology. Digital multimeters provide a yardstick with which we can quantify the actual voltage, current, and resistance or impedance relationships of any circuit.

Current through any circuit is measured by an analog or digital indicating instrument called an *ammeter* connected in series with the circuit to be measured. The ammeter is connected such that the current to be measured passes through the instrument. Therefore, the ammeter must be capable of carrying this current without damage or excessive loading effects. If the circuit is drawing current in the milliamperage range (10^{-3} amperes), it is useless to make the measurements with a 0 to 1 ampere meter.

The direct-current ammeter has two terminals marked (+) and (-). If the meter is connected such that current flows into the (+) terminal, the

meter will read properly up scale. If the direction of current flow is the opposite, the meter will read down scale. This can be corrected by simply reversing the two wires connected to the ammeter.

The voltage across any element or two points is measured by an indicating instrument called a *voltmeter* connected directly across (in parallel) the element or two points. The voltmeter, since it is connected in parallel (Figure 1.1), must have an input resistance large enough such that it does not affect the voltage value being measured. The analog voltmeter must be such that the instrument will not be damaged and the pointer should deflect as full scale as possible for highest accuracy. Such a problem does not exist with a digital multimeter. Digital multimeter measurements should be made as close as possible to full scale to minimize errors.

A good rule of thumb to use in making voltage measurements and to ensure a loading error of less than 5% is to utilize a voltmeter with an input resistance at least 20 times greater than the resistance of the element whose voltage we are measuring. The input resistance of the analog voltmeter or volt-ohm-milliamperemeter (VOM) is generally the ohms per volt multiplied by the maximum scale voltage or maximum scale voltage divided by the voltmeter current sensitivity. Digital multimeters have an input resistance typically of 10 megohms (M Ω) on dc volts.

In making any electrical or electronic measurement, the analog instrument used will have some specified accuracy. The accuracy is usually specified as a percent accuracy of full-scale reading. A meter that has a specified accuracy of $\pm 2\%$ will have a maximum error of $0.02 \times 100 \text{ V} = \pm 2 \text{ V}$ on the 100-V scale and a maximum error of $0.02 \times 10 = \pm 0.2 \text{ V}$ on the 10-V scale; the voltage error may be $12 \text{ V} \pm 2 \text{ V}$, so the actual percent accuracy is $2 \times (100/12) = 16.7\%$. If the voltmeter had a 20-V scale that was used, the maximum error would be $\pm 0.02 \times 20 = \pm 0.4 \text{ V}$. The percent error for a 12-V reading would be $\pm (0.4/12) \times 100 = 3.33\%$ instead of a maximum error of 16.7% on the 100-V scale.

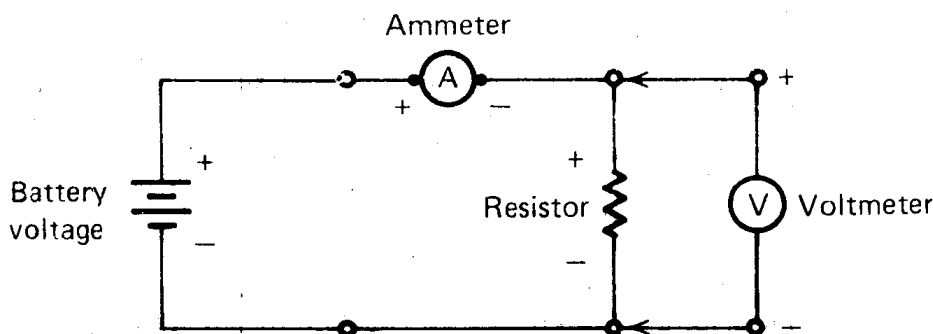


FIGURE 1.1

Direct-current ammeter and voltmeter connection in a series circuit.

1.2

THE DIGITAL MULTIMETER^a

The capability to measure and digitally display volts, ohms, and milliamperes [1,2] has been the basis of an entire industry for better than 15 years. While this is a relatively short period, the digital multimeter (DMM) industry has advanced at an incredible rate.

From the introduction of the first digital voltmeter in 1963 to the most complex systems meter of today, the digital multimeter business has always been on the leading edge of technology. Each new breakthrough in technology has resulted in products that perform better and cost less.

Following the introduction of the DMM, the industry went through a phase common to most newly born industries. Many companies went off in different directions, each trying to develop successful products. Methods such as mechanical decade counters driven by servomotors were developed. While such events now seem amusing, it is typical of a fledgling industry until a proved direction is established.

The DMM industry established the direction it was to follow in the late 1960s. At this time, the John Fluke Manufacturing Company introduced its first DMM, the 8100, whose price was high and performance not startling. The significance of this event was that a company known for quality test equipment entered the DMM business (see Figure 1.2).

During the late 1960s and early 1970s, electronic technology improved rapidly: the first operational amplifier was introduced; field-effect transistors became affordable; light-emitting diode (LED) readouts and digital-logic integrated circuits (ICs) became available; and large-scale integration (LSI) became practical.

Technology again intervened when LSI companies produced two-chip sets that would handle analog-to-digital (A/D) conversion. Firms such as Intersil and Siliconix began to offer reasonably priced precision A/D converters that functioned with a minimum of external components. These LSI A/D converters offered advantages in parts count and cost over the discrete A/D, which was used in the 8000A. Companies such as Keithley Instruments began to offer a complete line of DMMs based on these LSI A/D converters, which were low in cost and offered excellent performance.

Fluke, beginning to feel the effects of competition in the DMM marketplace, again made a move that would shake up the DMM business. They approached Intersil, a large manufacturer of FETs and monolithic A/D converters; together they developed a monolithic A/D converter that would become the basis for virtually every handheld DMM made today.

^aThe material in Section 1.2 is from George B. Tuma, "Digital Multimeters Historical Overview," *Measurements and Control*, Dec. 1980; and "Keithley Electronic Measurement Instrumentation Catalog Guide," courtesy of Keithley Instrument Co., Cleveland, Ohio.

Until this time A/D converters were based on NMOS technology. This meant high power consumption, which precluded battery operation. They also required regulated power supplies.

The Intersil A/D converter (known as the ICL 7106) (see Figure 1.3) is a $3\frac{1}{2}$ -digit single-chip A/D converter. Integrated in CMOS for low power consumption, it features direct liquid crystal drive and on-board power-supply regulators. It was designed to require a minimum of external components, and provides more than enough accuracy for $3\frac{1}{2}$ -digits.

Simultaneously, a complete line of low-power op-amps and precision references became available from Intersil. These further facilitated the design of handheld DMMs. Intersil granted one-year exclusive rights to the

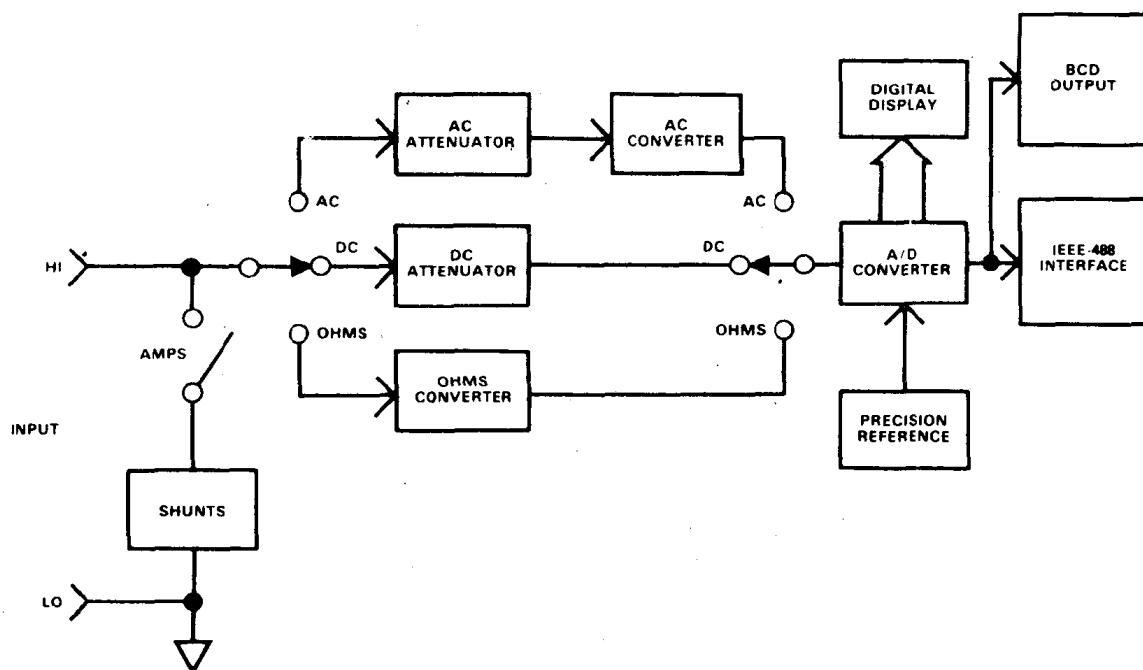


FIGURE 1.2

The specifics may vary, but all DMMs are designed around this basic architecture. The analog-to-digital (A/D) converter is the heart of every DMM design. Through one of a number of conversion techniques, a voltage input is accurately displayed on a digital readout. Circuitry is then developed to convert ohms, ac volts, or amperes into proper A/D input voltage. (Courtesy of Keithley Instrument Co.)

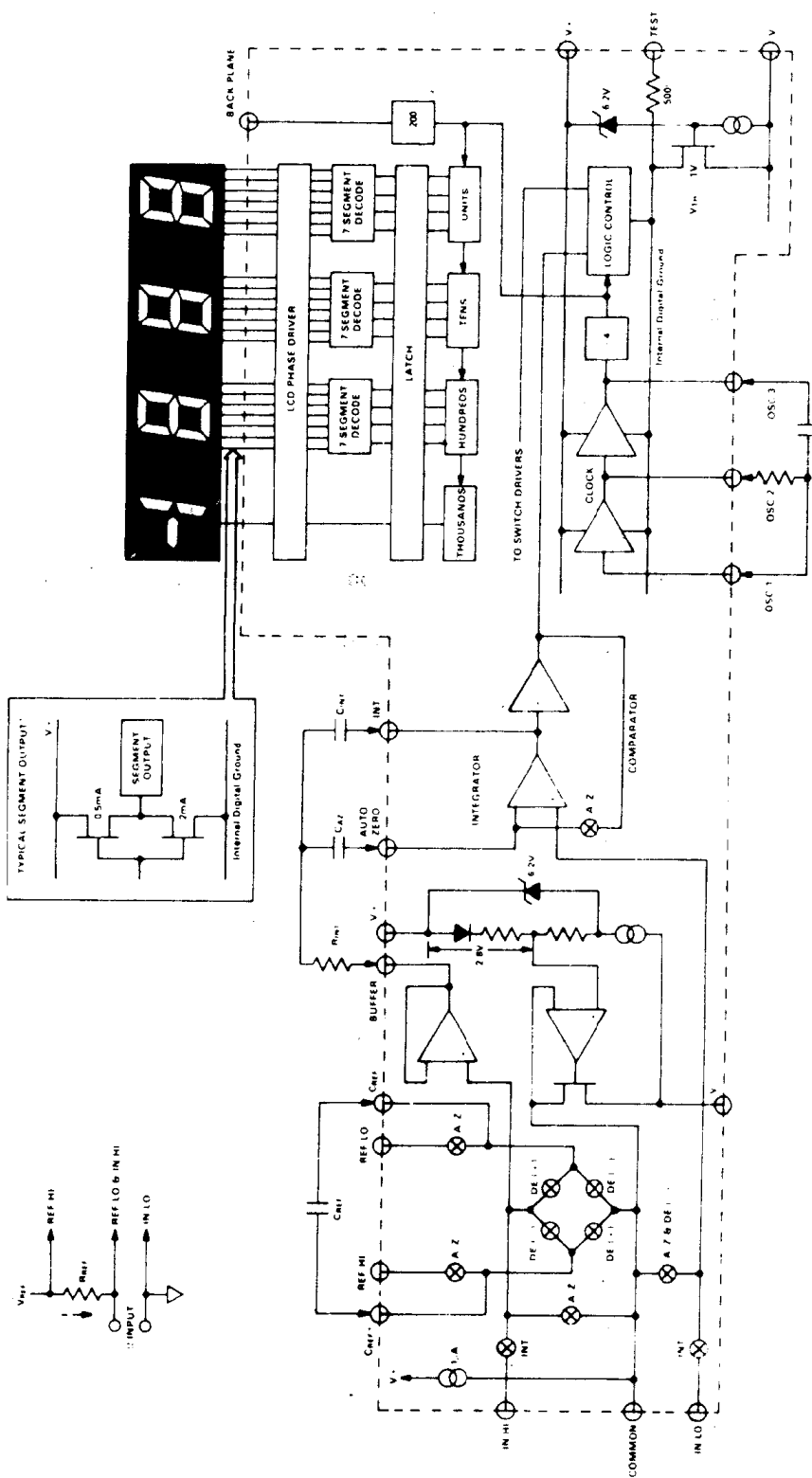


FIGURE 1.3

The Intersil ICL 7106 is a single-chip A/D converter that runs directly from a 9-V battery. Driving a liquid crystal display, the power consumption is about 1 mA. The input configuration can be used to measure ohms with no additional components. (Courtesy of Datal-Intersil, Inc.)

READING UNCERTAINTY			
VOLTAGE LEVEL	% OF FULL SCALE	3½ DIGITS $\pm (0.1\% + 1d)$	4½ DIGITS $\pm (0.1\% + 1d)$
1V	5%	1.1 %	0.2 %
5V	25%	0.3 %	0.12 %
10V	50%	0.2 %	0.11 %
19V	95%	0.15%	0.105%

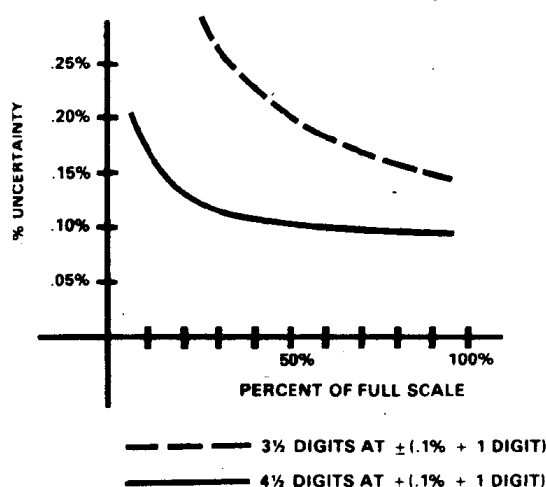
FIGURE 1.4

Reading uncertainty. (Courtesy of Keithley Instrument Co.)

7106 A/D converter, and Fluke immediately introduced the 8020, the world's first handheld DMM.

When the 7106 became available to the rest of the industry, it was a situation almost unique to the electronics industry; every DMM manufacturer had available the same design for a battery-powered DMM. At the heart of every DMM is the A/D converter, which converts an analog input signal to some kind of digital output. The digital output can be a 7-segment display, IEEE-488 standard interface, or the binary coded decimal (BCD) output. The A/D converter is largely responsible for the performance characteristics of any DMM.

Low-cost handheld DMMs use a single-chip, 3½-digit A/D converter.

**FIGURE 1.5**

Percent of uncertainty versus percent of full scale. (Courtesy of Keithley Instrument Co.)