Electronic Instrumentation

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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

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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 *bio*electronic 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.

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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 milliampere 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-milliampere meter (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 (MΩ) 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 ±2% will have a maximum error of 0.02 × 100 volts = ±2 V on the 100-V scale and a maximum error of 0.02 × 10 = ±0.2 V on the 100-V scale; the voltage error may be 12 V ± 2 V, so the actual percent accuracy is 2 × (100/12) = 16.7%. If the voltmeter had a 20-V scale that was used, the maximum error would be ± 0.02 × 20 = ±0.4 V. The percent error for a 12-V reading would be $\pm(\frac{0.4}{12}) \times 100$ = 3.33% instead of a maximum error of 16.7% on the 100-V scale.

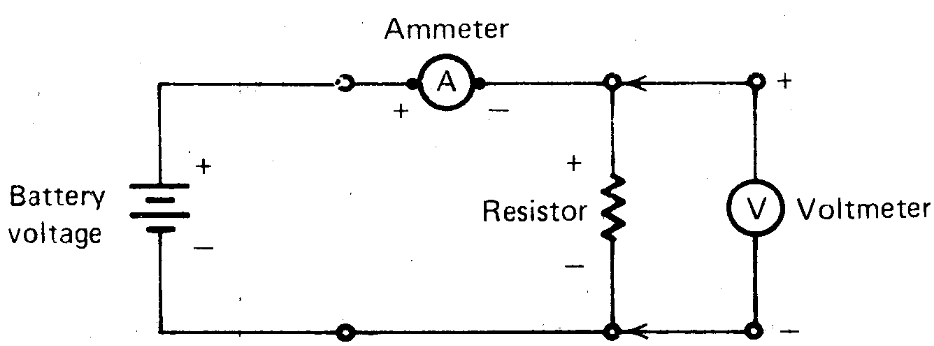

FIGURE 1.1
Direct-current ammeter and voltmeter connection in a series circuit.

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.

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[a] The 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

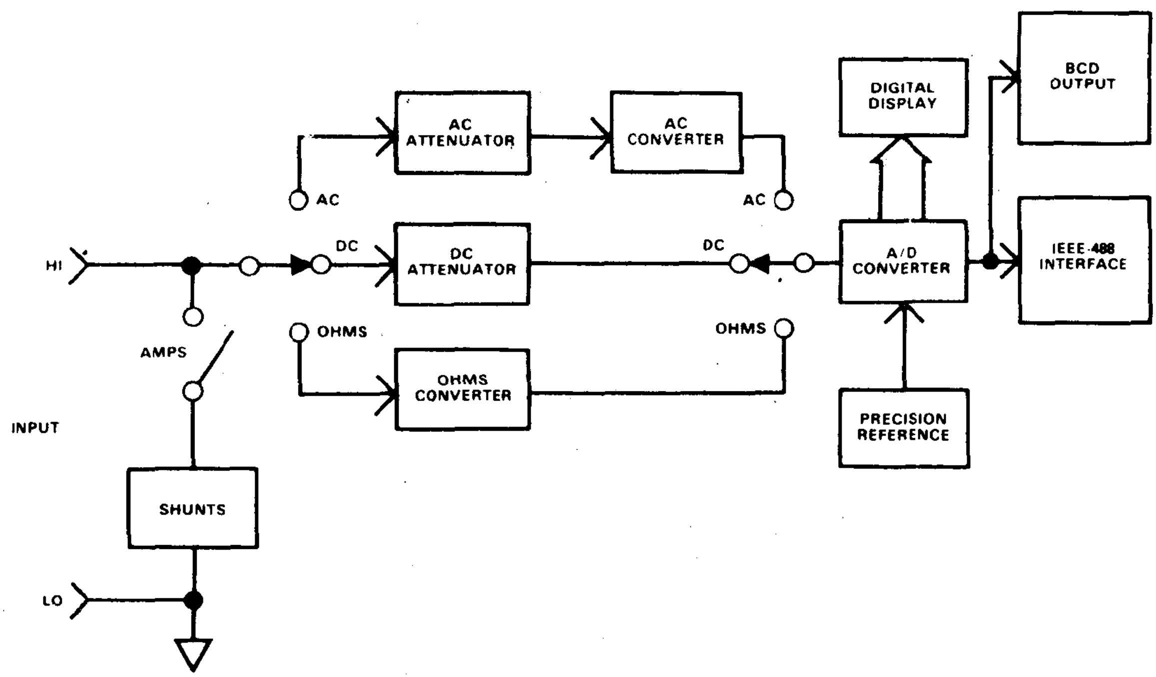

FIGURE 1.2
The specifics may vary, but all DMMs are designed around this basic architecture. The analog-to-digital (A/D) converter is the heart of every DMM design. Through one of a number of conversion techniques, a voltage input is accurately displayed on a digital readout. Circuitry is then developed to convert ohms, ac volts, or amperes into proper A/D input voltage. (Courtesy of Keithley Instrument Co.)

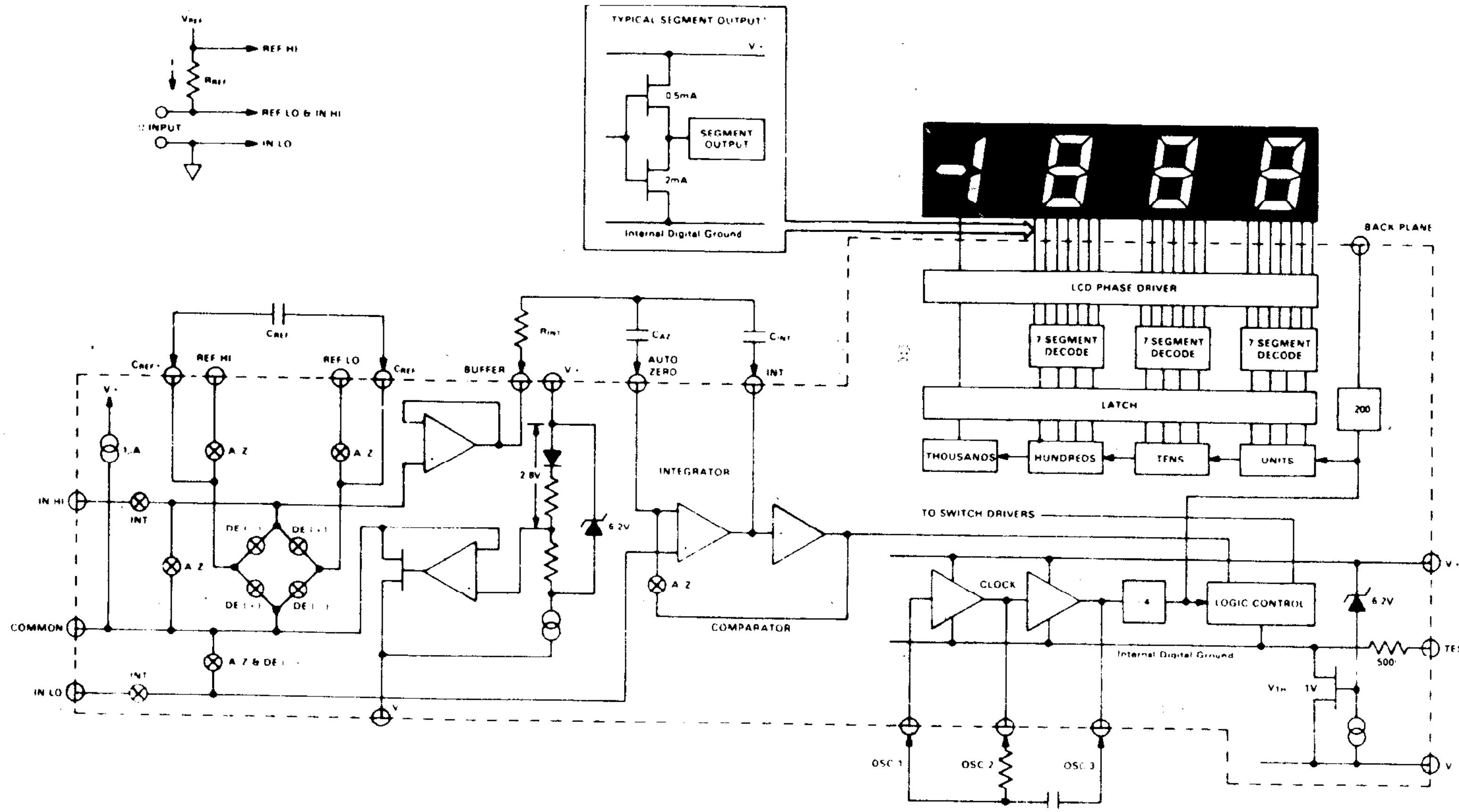

FIGURE 1.3
The Intersil ICL 7106 is a single-chip A/D converter that runs directly from a 9-V battery. Driving a liquid crystal display, the power consumption is about 1 mA. The input configuration can be used to measure ohms with no additional components. (Courtesy of Datel-Intersil, Inc.)

READING UNCERTAINTY

VOLTAGE LEVEL	% OF FULL SCALE	3½ DIGITS ±(0.1% + 1d)	4½ DIGITS ±(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.

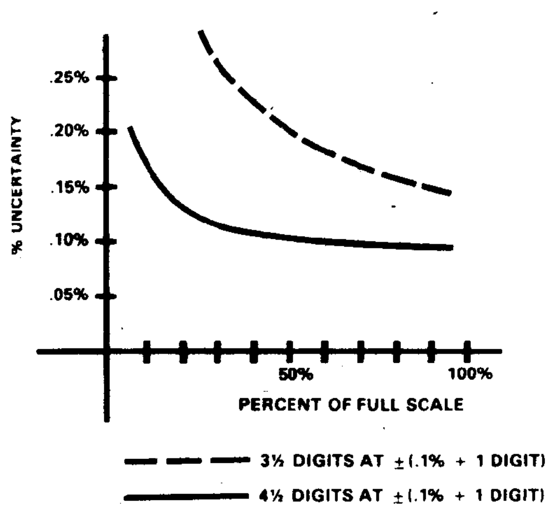

FIGURE 1.5
Percent of uncertainty versus percent of full scale. (Courtesy of Keithley Instrument Co.)