

**INSTRUMENTS
AND
MEASUREMENTS
FOR
ELECTRONICS**

INSTRUMENTS AND MEASUREMENTS FOR ELECTRONICS

CLYDE N. HERRICK

San Jose City College
San Jose, California

McGRAW-HILL BOOK COMPANY

New York San Francisco St. Louis Düsseldorf
Johannesburg Kuala Lumpur London Mexico
Montreal New Delhi Panama Rio de Janeiro
Singapore Sydney Toronto

This book was set in Times Roman by Holmes Typography, Inc., and printed and bound by The Maple Press Company. The designer was Janet Bollow; the drawings were done by Gary V. Baird. The editors were Alan W. Lowe and Eva Marie Strock. Charles A. Goehring supervised production.

**INSTRUMENTS
AND
MEASUREMENTS
FOR
ELECTRONICS**

Copyright © 1972 by McGraw-Hill, Inc. All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, without the prior written permission of the publisher.

Printed in the United States of America.

Library of Congress catalog card number: 79-152004

1234567890 MAMM 79876543210

07-28367-2

PREFACE

Electronics is a new and expanding field of scientific endeavor with many diverging areas, each changing rapidly, so that the devices we study and use today may soon be replaced by more sophisticated devices tomorrow. The electronic instrumentation used to make today's measurements will be replaced eventually with newer and more sophisticated instruments. However, there is a common core of knowledge threading through these areas, devices, and instruments.

It is the purpose of "Instruments and Measurements for Electronics" to provide the electronics technology student with a sound background in the basic theory and common-core concepts of measurements and electronic measuring instruments. To accomplish this purpose, the student is led through graduated measuring concepts and techniques using the measuring instrument as the supporting vehicle.

The student is also presented with a basic core of

measuring concepts and techniques through the study of electronic instruments. These instruments can be applied as the basis in every facet of measurement in electronics. Textual treatment includes both intuitive and descriptive approaches, as well as conceptual and analytic approaches.

The text provides the student with an understanding of the logic behind the selection of a specific type of instrument for a measurement and the accuracy to be expected from this instrument. The student will also learn the importance of proper care and application of each type of measuring instrument and the purpose of calibration and maintenance of this instrument. Careful distinction is made between accuracy and precision. The student will also obtain an understanding of the probability of error analysis for electronic instruments and measurements, and the limitation of each type of measuring instrument.

The foregoing objectives are realized in "Instruments and Measurements for Electronics" through the presentation of materials under six topics: Basic Measuring Instruments (Meters); Bridge-Type Instruments; Electronic Display Instruments; Generating Instruments; Tube and Semiconductor Device Testers; and Electronic Counters and Frequency Meters.

CLYDE N. HERRICK

CONTENTS

I

BASIC MEASURING INSTRUMENTS

I	PROBABILITY AND ERROR ANALYSIS	3
1.1	Precision of Measurements	3
1.2	Observational Errors	5
1.3	Errors of Estimation	6
1.4	Systematic Errors	7
1.5	Accuracy Ratings of Instruments	8
1.6	Other Accuracy Factors	10
1.7	Applications	13
	Questions and Problems	15

2	DC VOLTMETERS, AMMETERS, AND OHMMETERS	17
2.1	Introduction to Meters	17
2.2	D'Arsonval Meter Movement	18
2.3	Calibrated Galvanometers	22
2.4	Ammeters, Milliammeters, Microammeters, and Shunts	23
2.5	Voltmeter Multipliers	26
2.6	The Basic Ohmmeter	27
2.7	Aging of Permanent Magnets	29
2.8	Applications	30
	Questions and Problems	32
3	AC VOLTMETERS, AMMETERS, AND WATTMETERS	34
3.1	Classes of Meters	34
3.2	Basic AC Voltmeters	36
3.3	Iron-Vane AC Voltmeters	41
3.4	Electrodynamic AC Voltmeters	45
3.5	Frequency Capabilities of Basic AC Instruments	50
3.6	Applications	54
	Questions and Problems	56
4	VOLT-OHM-MILLIAMMETERS	58
4.1	Basic Requirements	58
4.2	Ranges and Subfunctions	59
4.3	Basic Types of Volt-Ohm-Milliammeters	68
4.4	Applications	71
	Questions and Problems	73
5	VOLT-OHM-MILLIAMMETER CIRCUITRY	76
5.1	Basic VOM	76
5.2	DC Voltage-Measuring Circuitry	77
5.3	AC Voltage-Measuring Circuitry	79
5.4	AC Voltmeter Function at $5000\ \Omega/V$	82
5.5	Output Meter Function	84
5.6	DC Current Function	85
5.7	Ohmmeter Function	86
5.8	Complete VOM Configuration	88
5.9	Meter Application Notes	88
5.10	VOM Maintenance	91

5.11	VOM Accessories	92
5.12	Applications	94
	Questions and Problems	95

6	VACUUM-TUBE VOLTMETERS	98
6.1	Advantages and Disadvantages of VTVM	98
6.2	The Vacuum-Tube Bridge	99
6.3	Multipliers and Bridge Configurations	105
6.4	Ohmmeter Configurations and Resistance Measurement	109
6.5	AC Voltage Measurement	111
6.6	Combination VOM-VTVM Instruments	115
6.7	Low-Range AC VTVM Instruments	117
6.8	Differential VTVM	124
6.9	Sensitive AC VTVM	125
6.10	Electrometer-Type VTVM	127
6.11	Applications	128
	Questions and Problems	133

7	TRANSISTOR VOLTMETERS	136
7.1	Advantages	136
7.2	Cascaded Transistors	138
7.3	Compensated Configurations	139
7.4	Transistor Bridge Circuits	141
7.5	FET Bridge Circuits	142
7.6	FET Input with Stabilizer Stage	147
7.7	Applications	151
	Questions and Problems	152

II

BRIDGE-TYPE INSTRUMENTS

8	RESISTANCE BRIDGES	157
8.1	Bridge Balance Requirements	157
8.2	Resistance Bridges	158
8.3	Resistance Measurement with the Wheatstone Bridge	160
8.4	Measurement of Small Resistance Values	163
8.5	Bridge-Type Indicating Instruments	164
8.6	Strain-Gage Bridge Configuration	167
8.7	Applications	169
	Question and Problems	169

9	CAPACITANCE BRIDGES	171
9.1	Bridge Voltage Requirements	171
9.2	Basic Capacitance Bridge	172
9.3	Power-Factor Measurement	173
9.4	Capacitance Bridge Classifications	175
9.5	Substitution Method of Capacitance Measurement	179
9.6	Series or Parallel Component Indication	181
9.7	Commercial Capacitance Bridges	181
9.8	Applications	183
	Questions and Problems	184
10	INDUCTANCE BRIDGES	186
10.1	Bridge Voltage Requirements	186
10.2	Characteristics of Typical Inductors	187
10.3	The Maxwell Bridge	189
10.4	The Hay Bridge	190
10.5	Incremental Inductance Bridge	190
10.6	Mutual Inductance Bridge	194
10.7	Standard Inductors	195
10.8	The Owen Bridge	198
10.9	Applications	199
	Questions and Problems	200
11	IMPEDANCE BRIDGES	202
11.1	Measuring Q and D Values	202
11.2	The Basic Impedance Bridge	203
11.3	Capacitance-Measuring Function	207
11.4	Inductance-Measuring Function	208
11.5	A Moderately Elaborate Impedance Bridge	211
11.6	Bridge Accuracy Ratings	215
11.7	Principles of Q Meters	217
11.8	Applications	221
	Questions and Problems	222

III

ELECTRONIC DISPLAY INSTRUMENTS

12	OSCILLOSCOPE PRINCIPLES AND THE BASIC OSCILLOSCOPE	225
12.1	Basic Measurements	225
12.2	The Cathode-Ray Tube	226

12.3	Operation of the Cathode-Ray Tube	229
12.4	The Basic Oscilloscope	231
12.5	Basic Oscilloscope Operation	233
12.6	Applications	240
	Questions and Problems	242

13	GENERAL-PURPOSE OSCILLOSCOPES	244
13.1	Time-Base Requirements	244
13.2	Principles of Time Base	245
13.3	Vacuum-Tube Time Bases	250
13.4	Solid-State Multivibrator	252
13.5	Asymmetrical Multivibrator	254
13.6	Time-Base Synchronization	256
13.7	Oscilloscope Amplifiers	259
13.8	Basic Oscilloscope Amplifiers	261
13.9	Solid-State Configurations	270
13.10	Basic Direct-Coupled Amplifier	278
13.11	Direct-Coupled Amplifiers in Cascade	280
13.12	First Horizontal Direct-Coupled Amplifier	282
13.13	Push-Pull Deflection	284
13.14	Second Horizontal Direct Coupled Amplifier	284
13.15	Horizontal Channel Used to Indicate DC Voltages	286
13.16	Vertical Amplifiers	287
13.17	Vertical Attenuator	288
13.18	Practical Attenuator	288
13.19	Vertical Cathode Follower	290
13.20	First Direct-Coupled Vertical Amplifier	290
13.21	Second Direct-Coupled Vertical Amplifier	291
13.22	Applications	292
	Questions and Problems	294

14	TRIGGERED-SWEEP OSCILLOSCOPES	296
14.1	Circuit Requirements	296
14.2	Circuit Operation	298
14.3	Calibrator Section	299
14.4	Vertical Attenuator	301
14.5	Vertical Amplifier	304
14.6	Pickoff Point for Time-Base Generator	305
14.7	Time-Base Trigger Section	306
14.8	Time-Base Generator Section	313
14.9	Horizontal Amplifier	323
14.10	Regulator Circuit	327

14.11	Amplifier Characteristics	333
14.12	Probes for Oscilloscopes	338
14.13	Applications	342
	Questions and Problems	348

15 OSCILLOGRAPHS AND XY RECORDERS 350

15.1	Basic Differences	350
15.2	Operation of Recording Voltmeter	352
15.3	Storage-Type Cathode-Ray Tube	355
15.4	Oscillographic Camera Equipment	356
15.5	Servo-Type XY Recorder	360
15.6	Applications	366
	Questions and Problems	366

IV

GENERATING INSTRUMENTS

16 AUDIO OSCILLATORS 371

16.1	Basic Requirements	371
16.2	Wien Bridge <i>RC</i> Oscillator	373
16.3	Bridged-T Oscillator	377
16.4	Phase-Shift Oscillator	379
16.5	Bridge-Type Phase-Shift Oscillator	381
16.6	Beat-Frequency Oscillators	381
16.7	Applications	384
	Questions and Problems	388

17 RF SIGNAL GENERATORS 390

17.1	Basic Requirements	390
17.2	Basic Configurations	391
17.3	Waveform Optimization	394
17.4	Frequency Stabilization	398
17.5	Modulation of the RF Signal	398
17.6	Attenuators for Signal Generators	401
17.7	Solid-State Generator	406
17.8	Grid-Dip Meters	411
17.9	Applications	415
	Questions and Problems	418

18 SWEEP-FREQUENCY GENERATORS 420

18.1	Basic Requirements	420
18.2	Basic Sweep Generator Characteristics	421

18.3	Development of a Frequency-Response Curve	422
18.4	Sweep Signal Generation	424
18.5	RF Output Considerations	426
18.6	Video-Frequency Sweep Signals	429
18.7	Complete TV-FM Sweep Generator	430
18.8	Marking the Response Curve	431
18.9	Solid-State FM Generator	435
18.10	Applications	442
	Questions and Problems	444

19 SQUARE-WAVE AND PULSE GENERATORS 446

19.1	Comparison of Square-Wave and Pulse Waveforms	446
19.2	Methods of Square-Wave Generation	447
19.3	Multivibrator Square-Wave Generator	451
19.4	Pulse Generation	460
19.5	Applications	463
	Questions and Problems	466



TUBE AND SEMICONDUCTOR DEVICE TESTERS

20	TUBE TESTERS	471
20.1	Basic Tests	471
20.2	Basic Tube-Testing Requirements	472
20.3	Laboratory-Type Tube Testers	482
20.4	Applications	486
	Questions and Problems	487

21	SEMICONDUCTOR DEVICE TESTERS	489
21.1	Basic Transistor Parameters	489
21.2	Basic Transistor Test Methods	491
21.3	Tunnel Diode Tests	493
21.4	Zener-Diode Test Configuration	494
21.5	Laboratory-Type Semiconductor Testers	495
21.6	Applications	506
	Questions and Problems	507

VI

**ELECTRONIC COUNTERS AND
FREQUENCY METERS**

22	ELECTRONIC COUNTERS AND DIGITAL VOLTMETERS	511
22.1	Basic Requirements	511
22.2	Binary Counting Processes	512
22.3	Binary to Decimal Conversion	517
22.4	Digital Voltmeters	518
22.5	Applications	529
	Questions and Problems	530
	INDEX	531



BASIC MEASURING INSTRUMENTS

1. 100
2. 100
3. 100

1

PROBABILITY AND ERROR ANALYSIS

1.1 PRECISION OF MEASUREMENTS

Although beginning students tend to confuse the *precision* of a measurement with the *accuracy* of a measured value, there is a basic distinction between these terms. For example, a battery or cell such as illustrated in Fig. 1.1 has a terminal voltage (strictly an electromotive force) that we call its true or actual voltage. Furthermore, this actual voltage value is not measurable, although we can approximate this value by careful measurement. The accuracy of a measurement denotes the extent to which we approach this actual value. Even the most careful measurements can establish an actual voltage value only within certain limits of accuracy. Of course, new and improved measuring techniques can narrow these accuracy limits.

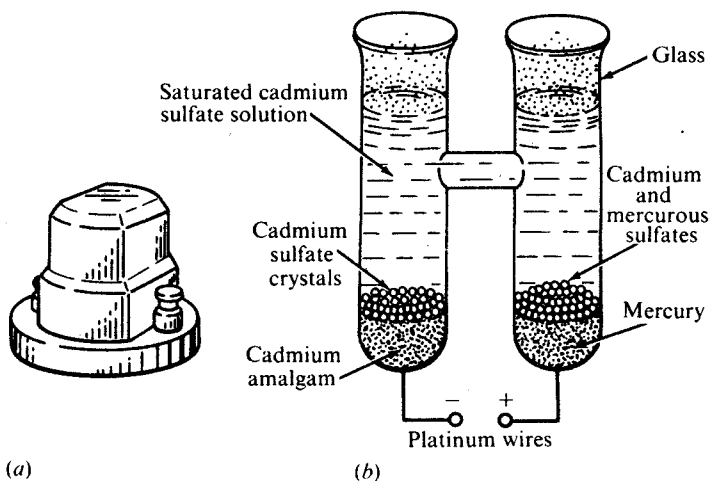


FIG. 1.1 Appearance (a) and construction (b) of a Weston standard cell.

On the other hand, the precision of a measurement denotes its departure from the average of a number of measured values. For example, suppose that we carefully measure the terminal voltage of a dry cell six times. Since an observational error is inevitably present in any voltmeter reading (except nonanalog types), we may take the precaution of asking five other observers to repeat this measurement and thus we have six separate measured values:

1.49	1.49
1.51	1.52
1.50	1.50

In this example, we are using the most accurate voltmeter available and accordingly are concerned only with the precision of the foregoing measurements. We proceed as follows: The *sum* of the measured values is 9.01 V. We divide this sum by 6 to find its *average value* of 1.50+ V. Since the remainder in the quotient is less than 5, we round off 1.50+ to 1.50 and thereby determine its *most probable value*. In turn, we conclude that the third and sixth measurements were the most precise within the group of six measurements.

Note that the first measurement has a precision of approximately 99.3 percent; this precision can also be stated as approximately +0.7 percent deviation from the mean. The third measurement has a precision of 100 percent, and so on. Next, if we obtain a voltmeter with a higher accuracy