

Electronics with Digital and Analog Integrated Circuits

RICHARD J. HIGGINS

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Preface

Most people who feel at home with electronics pick it up by osmosis over a long period. When I was an undergraduate, I sometimes got a ride to class from a professor who lived near my home. He discovered that I'd never heard of negative feedback, and was astounded that an undergraduate education at MIT could leave out so elegant a concept. As a graduate student, I saw feedback put to work when a clumsy motor-generator power supply for a high-current electromagnet was replaced with an array of power transistors driven by operational amplifiers. Currents of microamps were controlling hundreds of amps! In my PhD project I found that I could enhance fine-structure in some data by running the signal through an op amp differentiator, and discovered the fun of signal processing. Later, in my own lab, we began some measurements that were extremely tedious. We interfaced the experiment to a minicomputer, which didn't get bored or tired like we did. Microprocessors make even more experiments amenable to automation.

There is a great satisfaction in putting one's own circuit together and having it work just like the design predicted. Debugging has the fun of detective work, once one gets over the feeling of being a complete klutz with electronics. There's just one problem: how to learn it. Now that everyone can afford a small computer, there's a wider need for a background course on how to connect the computer to the experiment. IC's have made all this much simpler. The *black box* approach gets results, so one rarely needs to know what's inside the box. One doesn't need the kind of course taught for electrical engineers, which takes too long for most scientists and doesn't adequately emphasize user applications. That's what this book is all about: *using electronics without fear!*

This book includes in one volume both digital and analog integrated circuit instrumentation. Many microcomputer interfacing examples are given. For example, the treatment of flip-flops in Chapter 4 ends with a discussion of tri-state logic and microcomputer bus interfacing. Microcomputers as such are not treated in this book. The emphasis here is on *applications* of IC electronics in measurement, control, signal generation, and signal processing.

The *approach* is to jump right into a given area, developing the necessary background as needed. The *focus* is on circuit principles and theorems, developing powerful “golden rules” which will work in many applications and which will not become obsolete with evolving technology. Details of circuit design are avoided whenever possible. On the other hand, the inside workings of specific industry-standard IC’s are explained, and many applications with practical working circuits are included. Samples of IC specification sheets or tables are given, since it is important to learn how to read a “spec sheet” and select the right device.

The material in this book has served a primary *audience* of physics, computer science, chemistry, and biology students. It also has served students in other disciplines, attracted by the personal computer revolution, hi-fi electronics, or *Popular Electronics* tinkering projects. The material also can serve nonelectrical-engineering fields where electronic instrumentation is a present day necessity, or professionals whose electronics education came before IC’s. The *level* of the material is matched to an audience of both graduate and upper-division undergraduate students. Half the audience has typically been physicists. The other half has been mostly computer scientists, providing valuable hands-on hardware background for this discipline. Students from other fields such as chemistry, biology, geology, psychology, and, occasionally, even music, business, architecture, urban planning, broadcasting, and physical education have used this material, with the math suitably scaled down.

The *background* of these students has varied widely. For many, this is the first time they have seen a differential equation, or have used complex numbers. The only necessary *electronics* background is Ohm’s law, simple network theory, and a bit about discrete components like capacitors and transistors. A chapter on discrete component and semiconductor device electronics is provided for students without this background. The only math background needed for two-thirds of the book is enough introductory calculus to know how to recognize a derivative or an integral. Complex numbers are developed in an appendix. Students seem to pick up the math as it is introduced in context, and are motivated to learn more math by seeing its usefulness.

The text material has been developed into two independent one-term mini-courses. Chapters 1 to 9 form a manageable unit on digital IC electronics, with Chapter 9 (Digital to Analog and Analog to Digital Conversion) forming a bridge to the analog world. Chapters 10 to 20 form an analog IC electronics course. Enough additional material is provided to add flexibility for semester-long courses, varying background, or instructor’s preference. For example, students without *any* prior electronics background should cover Chapter 1, The Basics: Discrete Component Circuits and Measurements.

The level varies greatly but systematically. I originally taught the analog material first because one then has the background to understand digital waveshaping and analog-to-digital and digital-to-analog conversion. However, the mathematics is much easier in the digital material, and the labs tend to be much more foolproof, so learning this part first is much more painless. The analog portion begins at a low math level, but includes several sections requiring some familiarity with differential equations, a willingness to become at home in the complex plane, and to learn the Laplace transform. These more difficult sections in Chapters 14, 16, 17, and 19 are marked with a † and are really only suitable for an upper division or graduate student audience of science or engineering majors.

This book came about after teaching an “electronics for scientists” course over a period of four years, using such standard texts as Brophy’s *Basic Electronics for Scientists*, Diefenderfer’s *Principles of Electronic Instrumentation*, or Malstadt *et al* *Electronic Measurements for Scientists*. Although written at the appropriate level for scientists, each had some disadvantages. Most did not go far enough in applications to bring the student to the point of working with state-of-the-art instrumentation. None of the standard texts used specific industry-standard IC devices, such as a 741 op amp or 7400 series TTL, to prepare the user to design and construct practical circuits. Recently, hobbyist-level publications have appeared which are organized as cookbooks. The user can jump right in and do surprisingly powerful tricks with very little previous electronics background. Examples include Larsen and Rony’s *Bug Books*, Melen and Garland’s *Understanding IC Op Amps* and Lancaster’s *TTL Cookbook* (and *CMOS Cookbook*). Our trials of such material in the laboratory were successful in stimulating students’ interest in what was really possible with IC’s. Nonetheless, there were considerable gaps at the level of *why* things work (as to be expected from the cookbook approach) which were unsatisfying for an audience of college-level scientists. In addition, none of these books had enough applications for the sciences, particularly in measurement, control, and signal processing. This book is a combination of the best features of both the “electronics for scientists” and “hobbyist” or “cookbook” approach.

Laboratory experiments are the key to feeling at home with electronics. The textbook knowledge is useless unless one has wired together circuits and gotten them to work. A separate volume of lab experiments, *Experiments with Integrated Circuits*, is available to accompany this text. It is hard to convey to the newcomer how easy it is to get started in electronics these days. The inertia to learn about IC’s disappears rapidly once one has had success with a few experiments that one can do on the kitchen table. IC’s have made electronics both powerful and cheap. A kit of parts, illustrated in Chapter 2, which is sufficient to try out any of the ideas in this book, can be put together for about \$200, and test instruments (except for an oscilloscope) cost little more. Buy it, try it, and have fun with electronics, rather than just being surrounded by it!

It was Henry Paynter of M.I.T. who first introduced me to what could be done with negative feedback, and J. H. Condon who, as a fellow grad student, encouraged me to try out an op amp in physics signal processing. The IC manufacturers have made valuable contributions in developing the state of the art with

their applications literature, especially National Semiconductor, Texas Instruments, Signetics, RCA, Motorola, Analog Devices, Philbrick, and Burr Brown. Some of those contributions are extracted here. I have profited especially from D. H. Sheingold, Analog Devices, whose writing captures the sense of wonder one feels when an idea comes out of one's head and onto a circuit board and works well.

Nearly a decade of teaching assistants helped to develop the course on which this book is based. I am especially indebted to Hal Alles, Gary Karshner, and Tom Matheson. Margaret Graff gave editorial help with ruthless precision. Numerous typists (Liz Rachman, Sharon Robbins, Dolly Allen, Marc Baber, Linda Ficere, and Bev Jeness) put up with many revisions. The preparation of this manuscript, and especially the editing to incorporate helpful suggestions of several reviewers, was greatly facilitated by the Word Star (©Micropro International) word processing program.

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R. J. H.

Acronyms and abbreviations

a	ampere, unit of current OR op amp open loop gain	F	farad, unit of capacitance
AC	alternating (oscillatory) current or voltage	FET	field-effect transistor
A/D or ADC	analog to digital converter	FF	flip flop
AM	amplitude modulation	FG	function generator
AND, OR	gates which perform logic AND/OR function	FIFO	first in, first out
BIN	binary (base 2)	FLAG	device status signal (ready/not ready)
BCD	binary-coded decimal	FM	frequency modulation
BiFET	bipolar plus field-effect transistors on the same IC	FS	full scale
BiMOS	bipolar plus MOS transistors on the same IC	FSK	frequency-shift keying
BP	band-pass	FT	Fourier transform
C	a capacitor	GND	ground connection
CCD	charge-coupled device	H	henry, unit of inductance
CLK	clock	HEX	hexadecimal (base 16)
CMOS	complementary (both p-channel and n-channel) MOS	HP	high-pass
CMRR	common mode rejection ratio	Hz	hertz, unit of frequency (= cycles/sec)
CNTL	control	IC	integrated circuit
CNTR	counter	I _{co}	reverse-bias transistor leakage current
CPU	central processing unit	I/O	input/output
CS	chip-select	Im	imaginary part of a complex number
CV/CC	constant voltage/constant current	JFET	junction field-effect transistor
D	data or data input	JK	type of flip flop with no disallowed states
D/A or DAC	digital to analog converter	L	an inductor
dB	decibel	LP	low pass
DC	direct (nonoscillatory) current or voltage	LSB	least significant bit
DMM	digital multimeter	LSI	large-scale integration
DMPX	demultiplex	MOS	metal-oxide semiconductor
DTL	diode-transistor logic; made obsolete by TTL	MOSFET	metal-oxide-semiconductor field-effect transistor
VM	digital voltmeter	MPU	microprocessor unit
ECL	emitter-coupled logic	MPX	multiplex
EEPROM	electrically erasable PROM	MPY	multiplier
EPROM	erasable programable read-only memory	MS	master-slave type of flip flop
		MSB	most significant bit
		MSI	medium-scale integration
		NAND, NOR	AND/OR gates with inverted outputs

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NF	noise figure	S/H or SH	sample and hold
OC	open circuit	SIPO	serial in, parallel out
OCT	octal (base 8)	SISO	serial in, serial out
Ω	ohm, unit of resistance	S/N	signal to noise
op amp	operational amplifier	SPDT	single pole, double throw 2-position switch
OS	one shot (monostable multivibrator)	SR	shift register (sometimes, set-reset flip-flop)
OTA	operational transconductance amplifier	STROBE	timing signal in handshaking
PIPO	parallel in, parallel out	SW	switch
PISO	parallel in, serial out	SYNC	synchronization
PLL	phase-locked loop	TG	transmission gate
p-p	peak-to-peak	TRIG	trigger or device activation
PROM	programmable read-only memory	TRI-STATE	tri-state logic: high, low or dis- connected
PSD	phase-sensitive detector = lock-in	TTI	transistor-transistor logic (bipolar)
Q	quality factor, of an inductor or band pass filter	UART	universal asynchronous receiver- transmitter
R	a resistor	V	volts, unit of voltage
RAM	random access memory (volatile, in current usage)	V_{cc}	collector power supply voltage
RDY	ready	VCG	voltage-controlled gain
RE	real part of a complex number	VCO	voltage-controlled oscillator
Ref	reference: stable source of voltage or current	V_{dd}	drain power supply voltage
RF	radio frequency range (~ 0.5 MHz and above)	V/F	voltage-to-frequency converter
rms	root mean square	VOM	volt-ohm-meter
ROM	read-only memory	VTVM	vacuum tube voltmeter (obsolete)
SC	short circuit	WR	write
SCOPE	oscilloscope	M	multiplier
SCR	silicon controlled rectifier	X	multiplier
SEL	select	XOR	exclusive or gate

Abbreviations of size or scale

10^{-3}	m milli-	10^{+3}	K kilo-
10^{-6}	μ micro-	10^{+6}	M mega-
10^{-9}	n nano-	10^{+9}	G giga-
10^{-12}	p pico-	10^{+12}	T tera-
10^{-15}	f femto-		

Contents

PREFACE *xi*

I THE BASICS: DISCRETE COMPONENT CIRCUITS AND MEASUREMENTS *1*

- 1.1 Measuring volts, amps, and ohms *1*
- 1.2 Principles for the analytical toolbox *4*
- 1.3 Theorems for the analytical toolbox *8*
- 1.4 Complex impedance and filter circuits *12*
- 1.5 Step response of passive networks *19*
- 1.6 P-type and N-type semiconductors *21*
- 1.7 Diodes and power supplies *22*
- 1.8 Junction (bipolar) transistors *28*
- 1.9 Field effect transistors *30*
- 1.10 FET voltage amplifier *33*
- 1.11 Common-emitter amplifier *38*
- 1.12 Common-collector amplifier or emitter follower *40*
- 1.13 SCR's *41*
- 1.14 Transducers *42*

2 BINARY NUMBERS AND DIGITAL INTEGRATED CIRCUITS *51*

- 2.1 Introduction *51*
- 2.2 Binary electronic devices and binary numbers *53*
- 2.3 Binary word length and the resolution of measurement or computation *58*
- 2.4 Representation of integers *60*
- 2.5 Working with integrated circuits *62*

8650275

3	GATES AND DIGITAL LOGIC	66
3.1	Electrical switching and mathematical logic	66
3.2	How to make a gate: DTL and TTL gate circuits	68
3.3	MOS gates	74
3.4	Logic circuits using gates	78
3.5	Boolean algebra	84
3.6	The exclusive OR and its applications	85
3.7	Gates as decoders, selectors, and multiplexers	91
3.8	TTL-CMOS gate comparison and interfacing between logic families	98
4	FLIP FLOPS	107
4.1	Discrete component flip flops	107
4.2	Flip flops from gates	109
4.3	Clocked flip flops	113
4.4	Master-Slave TTL Flip Flops	115
4.5	Edge-triggered TTL flip flops	120
4.6	CMOS flip flops	122
4.7	Tri-state logic and microcomputer bus interfacing	127
5	COUNTERS AND SHIFT REGISTERS	136
5.1	Basic counter circuits and specifications	137
5.2	TTL counters	142
5.3	MOS counters	148
5.4	Shift register circuits	157
5.5	TTL and CMOS shift register examples	161
5.6	Shift register applications	164
6	DIGITAL WAVESHAPING AND INSTRUMENTATION	178
6.1	Introduction	178
6.2	Digital waveshaping circuits	182
6.3	Waveshaping applications in microcomputer interfacing	196
6.4	Digital instrumentation	200
7	MEMORY	209
7.1	Introduction: The older I get, the more I can afford to remember	209
7.2	Memory types and terminology	212
7.3	Metal-oxide-semiconductor RAM	220
7.4	Read-only memories	228
8	BINARY ARITHMETIC	239
8.1	Binary addition software and hardware	240
8.2	2's complement subtraction	248
8.3	The software and hardware of binary multiplication	250

9	DIGITAL TO ANALOG AND ANALOG TO DIGITAL CONVERSION	258
9.1	Introduction: Bridging the gap to the real world	258
9.2	Digital to analog converter circuits	261
9.3	D/A applications	268
9.4	Comparing the features of A/D conversion methods	273
9.5	Dual slope A/D converter	275
9.6	Successive approximation A/D converter	279
9.7	Miscellaneous A/D methods	285
10	DIFFERENTIAL AMPLIFIERS AND THE MAGIC OF FEEDBACK	296
10.1	Introduction	296
10.2	The basic differential amplifier	296
10.3	A negative feedback example: unbypassed emitter resistor	298
10.4	Desired features of a differential amplifier	300
10.5	The solution: Balanced differential amplifier	301
10.6	Current source biasing and the origin of op amp bias current	302
10.7	The magic of feedback	304
10.8	Feedback methods	310
10.9	Stability problems	314
11	BASIC OP AMP APPLICATIONS	318
11.1	Weighted adder	319
11.2	Subtractor	320
11.3	Integrator	321
11.4	Differentiator	323
11.5	The transfer function concept	324
11.6	Application of the transfer function concept	326
11.7	Applications of the noninverting connection	328
12	OPERATIONAL AMPLIFIER REALITIES: THE NONIDEAL OP AMP	335
12.1	Interpreting op amp specifications	335
12.2	Internal circuitry of general purpose IC op amps	339
12.3	High performance IC op amps	349
12.4	Errors due to input voltage offset and bias current	353
12.5	Integrator drift due to nonideal op amp behavior; the premium op amp	358
12.6	Common mode errors	363
13	OP AMP APPLICATIONS IN REGULATION AND CONTROL	370
13.1	Voltage regulator	370
13.2	Current regulators	373
13.3	Commercial regulated power supplies	376
13.4	IC voltage regulators	381
13.5	Voltage-controlled resistor	384
13.6	The regulation of physical variables	386

14	OPERATIONAL NOTATION AND LINEAR SIMULATION	393
14.1	Operational notation	393
14.2	Application example: Integrator	395
14.3	Example of operational notation: Differentiator with a cutoff	396
14.4	The frequency domain and complex algebra	397
14.5	Application of operational notation: Integrator drift	397
14.6	Other examples of operational notation	399
14.7	Mathematical and electronic analogs	402
14.8	Analog solution of the damped harmonic oscillator	403
14.9	Stability	408
14.10	The complex s-plane view and the characteristic equation of a system	410
15	NONLINEAR ANALOG CIRCUITS	414
15.1	Diodes as switches: Precision ac voltmeters	414
15.2	Diode function generators	418
15.3	Logarithmic amplifiers	421
15.4	Multipliers and their applications	426
15.5	Summary of multiplier methods	428
15.6	A guide to multiplier terminology	430
15.7	Multiplier methods	431
15.8	Multiplier gymnastics	439
15.9	Multipliers in simulation	440
16	ACTIVE FILTERS	448
16.1	Introduction	448
16.2	Low-pass active filters	451
16.3	High-pass active filters	455
16.4	Bandpass active filters	455
16.5	Notch active filters	462
17	OSCILLATORS AND FUNCTION GENERATORS	465
17.1	Oscillator design ideas and methods	465
17.2	RC feedback oscillators	469
17.3	Tuned circuit oscillators	476
17.4	Sweep generator	478
17.5	Function generators	480
17.6	Commercial function generators	482
17.7	Integrated circuit function generators	485
18	THE MEASUREMENT OF SMALL SIGNALS	495
18.1	Noise and its origins	495
18.2	Instrumentation amplifiers	503
18.3	Coherent detection methods: Chopper stabilized and lock-in amplifiers	506
18.4	Phase-locked loops	515
19	ANALOG SWITCHING AND DIGITAL FILTERING	527
19.1	Comparators	527
19.2	Closed-loop tracking circuits	535
19.3	FET analog switches	540
19.4	Analog multiplexer applications	545
19.5	Sample and hold	551
19.6	Discrete time analog signal processing	556
19.7	Digital filters	566

APPENDIX 1	Powers of 2	571
APPENDIX 2	Some Guidelines for Beginners on Oscilloscope Use	573
APPENDIX 3	Complex Numbers	584
APPENDIX 4	Fourier Spectral Analysis	588
ANNOTATED BIBLIOGRAPHY		594
INDEX		599

1

The Basics: Discrete Component Circuits and Measurements

This chapter is one person's view of what one still needs to know about discrete component circuits, plus a bit about basic measurement techniques. As electronics has evolved towards a "black box approach," circuit design has become simpler. One does not need to know a lot about equivalent circuit models for transistors if most transistor properties drop out of the final result, as they do for two-state binary devices or high-gain analog devices. But even though most electronics is now done with IC's, one still needs to know how to use a discrete transistor, for example to drive a light-emitting diode or other high-current device. In addition, there are some fundamental principles which allow you to make giant steps in understanding circuits, such as the notion that almost any two-terminal black box can be treated as if it were just a signal source and a resistor. The chapter closes with sections on what discrete devices look like, examples of how to convert a "real world" quantity into an electrical signal, and a discussion of what instruments one needs for basic electronic measurements.

1.1 MEASURING VOLTS, AMPS, AND OHMS

1.1.1 *The Moving-Coil Meter*

Inside the basic analog or moving-pointer meter [Fig. 1.1(a)] are a coil of wire forming an electromagnet and a permanent magnet at right angles. When a current I is passed through the coil, a torque T_I is created, which is balanced by a restoring torque T_S from the suspension spring. Since $T_I = \text{const} \times I$ and $T_S =$

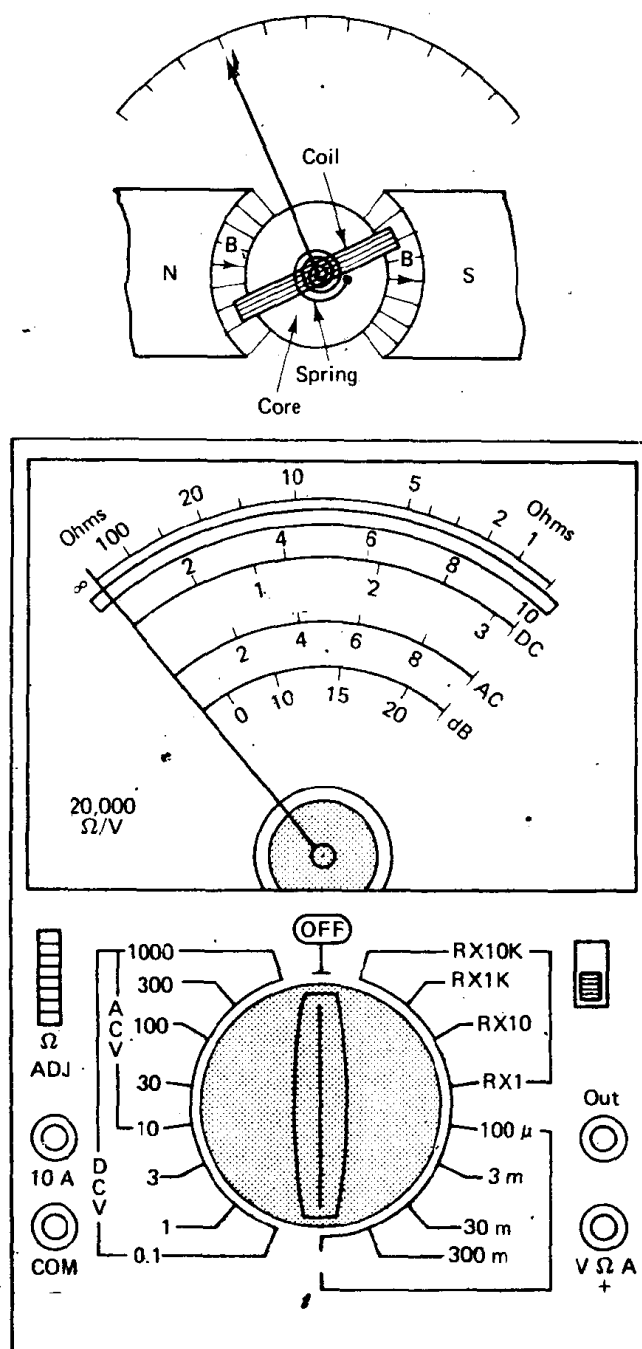


Figure 1.1 Instruments for measuring voltage, current, and resistance.
(a) Inside the moving-coil analog meter.
(b) Volt-ohm meter or VOM.

$k\theta$, the coil rotates and the two torques balance. The output angle is proportional to the input current being measured, and the basic meter circuit is a current sensor. Other applications require external circuitry to convert the quantity being measured to a current. The meter movement may be modeled as an ideal current meter, in series with a resistance equal in value to the resistance of the moving coil [Fig. 1.2(a)]. Typical parameter values are: full-scale meter deflection $I_m = 50 \mu A$, and meter resistance $R_m = 100 \Omega$.

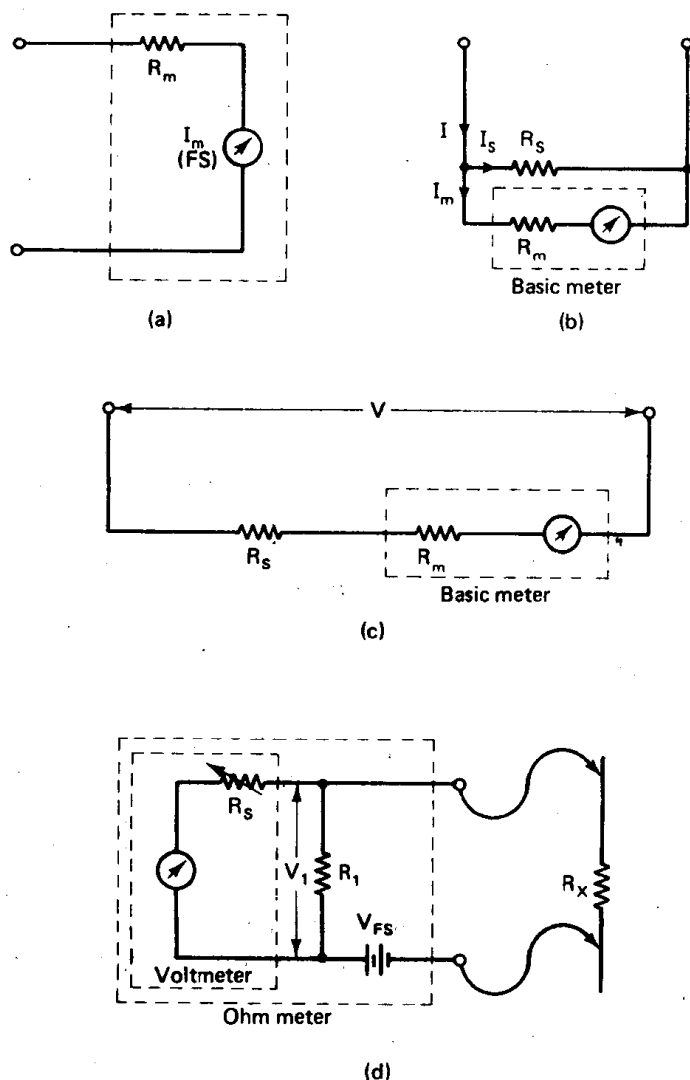


Figure 1.2 VOM circuits.
 (a) Equivalent circuit of the moving-coil meter. (b) Ammeter circuit.
 (c) Voltmeter circuit. (d) Ohmmeter circuit.

1.1.2 Volt-Ohm Meter Circuits

The moving-coil meter can measure current, voltage, or resistance. These functions are often combined in a basic test instrument called the *volt-ohm meter* (VOM). The measurement of currents larger than the basic meter's full-scale value requires diverting away most of the current (or else the meter will be destroyed) by placing in parallel a *shunt resistor* R_s [Fig. 1.2(b)]. R_s is selected so when the total input current equals the intended full-scale value, the meter is deflected to full-scale. Thus, for example, to measure 1-A full-scale requires a resistance $R_s = 0.5 \times 10^{-2} \Omega$ for the 50- μ A, 100- Ω meter described above. (Why?)

The same basic meter may be used to measure a voltage, provided that an extra series resistance is inserted so the desired full-scale voltage results in a full-scale meter current [Fig. 1.2(c)]. To create a 1-V full-scale meter with the basic meter above requires a 20-K Ω resistor in series. (Why?)

The VOM measures resistance by a comparison method. The unknown resistor forms a voltage divider with an internal standard resistor R_1 [Fig. 1.2(d)].