Electronics with Digital and Analog Integrated Circuits

RICHARD J. HIGGINS

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University of Oregon, Eugene

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

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

Abbreviations of size or scale

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

Contents

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 = const × I and T_S =

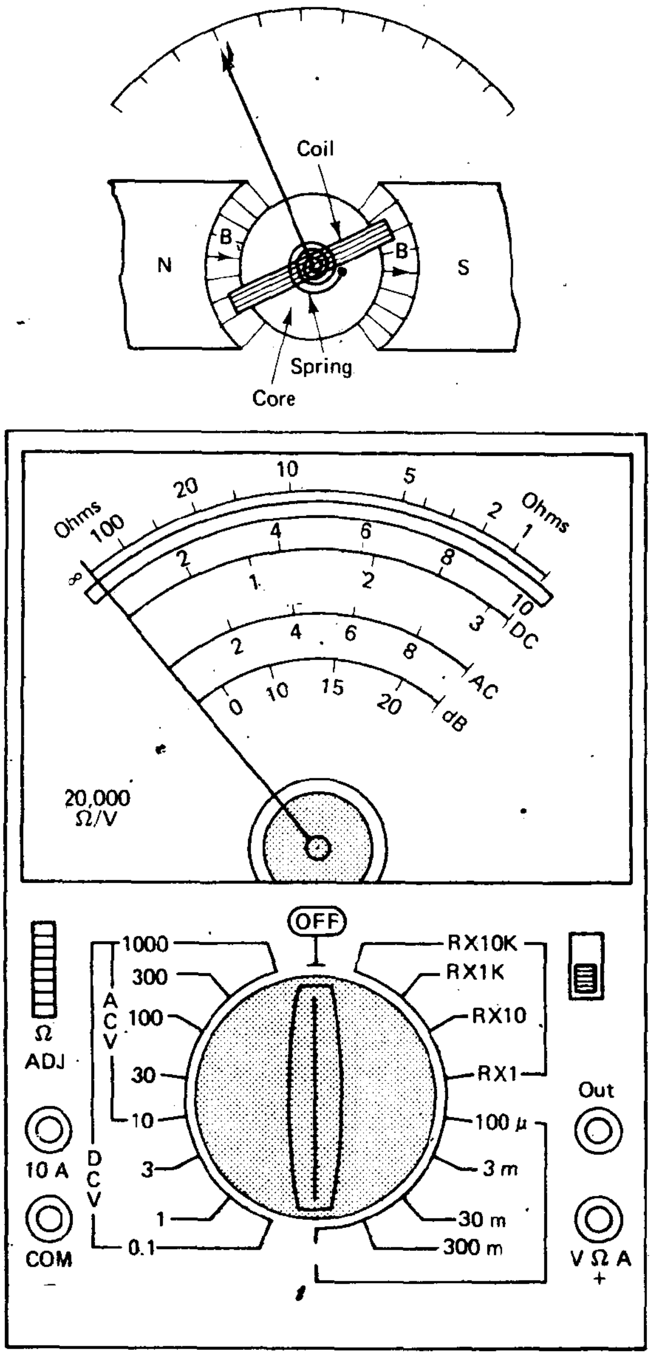

Figure 1.1 Instruments for measuring voltage, current, and resistance.
(a) Inside the moving-coil analog meter.
(b) Volt-ohm meter or VOM.

$k\theta$, 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 $R_m = 100\ \Omega$.

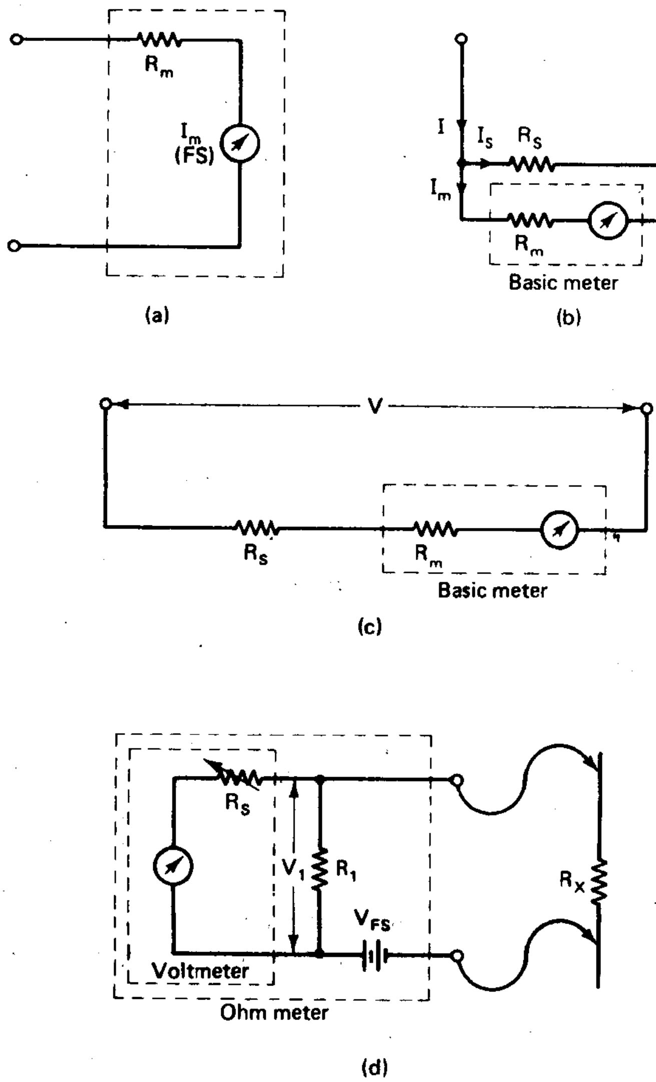

Figure 1.2 VOM circuits.
(a) Equivalent circuit of the moving-coil meter. (b) Ammeter circuit.
(c) Voltmeter circuit. (d) Ohmmeter circuit.

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-μA, 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-KΩ 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)].