

Digital Electronics

Principles, Devices and Applications

Anil K. Maini

Defence Research and Development Organization (DRDO), India



John Wiley & Sons, Ltd

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West Sussex PO19 8SQ, England
Telephone (+44) 1243 779777

Email (for orders and customer service enquiries): cs-books@wiley.co.uk
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John Wiley & Sons Canada Ltd, 6045 Freemont Blvd, Mississauga, ONT, Canada L5R 4J3
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Anniversary Logo Design: Richard J. Pacifico

Library of Congress Cataloging in Publication Data

Maini, Anil Kumar.

Digital electronics : principles, devices, and applications / Anil Kumar Maini.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-470-03214-5 (Cloth)

1. Digital electronics. I. Title.

TK7868.D5M275 2007

621.381—dc22

2007020666

British Library Cataloguing in Publication Data

A catalogue record for this book is available from the British Library

ISBN 978-0-470-03214-5 (HB)

Typeset in 9/11pt Times by Integra Software Services Pvt. Ltd, Pondicherry, India

Printed and bound in Great Britain by Antony Rowe Ltd, Chippenham, Wiltshire

This book is printed on acid-free paper responsibly manufactured from sustainable forestry in which at least two trees are planted for each one used for paper production.

In the loving memory of my father, Shri Sukhdev Raj Maini, who has been a source of inspiration, courage and strength to me to face all challenges in life, and above all instilled in me the value of helping people to make this world a better place.

Anil K. Maini

Contents

Preface	xxi
1 Number Systems	1
1.1 Analogue Versus Digital	1
1.2 Introduction to Number Systems	2
1.3 Decimal Number System	2
1.4 Binary Number System	3
1.4.1 Advantages	3
1.5 Octal Number System	4
1.6 Hexadecimal Number System	4
1.7 Number Systems – Some Common Terms	4
1.7.1 Binary Number System	4
1.7.2 Decimal Number System	5
1.7.3 Octal Number System	5
1.7.4 Hexadecimal Number System	5
1.8 Number Representation in Binary	5
1.8.1 Sign-Bit Magnitude	5
1.8.2 1's Complement	6
1.8.3 2's Complement	6
1.9 Finding the Decimal Equivalent	6
1.9.1 Binary-to-Decimal Conversion	6
1.9.2 Octal-to-Decimal Conversion	6
1.9.3 Hexadecimal-to-Decimal Conversion	7
1.10 Decimal-to-Binary Conversion	7
1.11 Decimal-to-Octal Conversion	8
1.12 Decimal-to-Hexadecimal Conversion	9
1.13 Binary–Octal and Octal–Binary Conversions	9
1.14 Hex–Binary and Binary–Hex Conversions	10
1.15 Hex–Octal and Octal–Hex Conversions	10
1.16 The Four Axioms	11
1.17 Floating-Point Numbers	12
1.17.1 Range of Numbers and Precision	13
1.17.2 Floating-Point Number Formats	13

Review Questions	17
Problems	17
Further Reading	18
2 Binary Codes	19
2.1 Binary Coded Decimal	19
2.1.1 BCD-to-Binary Conversion	20
2.1.2 Binary-to-BCD Conversion	20
2.1.3 Higher-Density BCD Encoding	21
2.1.4 Packed and Unpacked BCD Numbers	21
2.2 Excess-3 Code	21
2.3 Gray Code	23
2.3.1 Binary–Gray Code Conversion	24
2.3.2 Gray Code–Binary Conversion	25
2.3.3 <i>n</i> -ary Gray Code	25
2.3.4 Applications	25
2.4 Alphanumeric Codes	27
2.4.1 ASCII code	28
2.4.2 EBCDIC code	31
2.4.3 Unicode	37
2.5 Seven-segment Display Code	38
2.6 Error Detection and Correction Codes	40
2.6.1 Parity Code	41
2.6.2 Repetition Code	41
2.6.3 Cyclic Redundancy Check Code	41
2.6.4 Hamming Code	42
Review Questions	44
Problems	45
Further Reading	45
3 Digital Arithmetic	47
3.1 Basic Rules of Binary Addition and Subtraction	47
3.2 Addition of Larger-Bit Binary Numbers	49
3.2.1 Addition Using the 2's Complement Method	49
3.3 Subtraction of Larger-Bit Binary Numbers	52
3.3.1 Subtraction Using 2's Complement Arithmetic	53
3.4 BCD Addition and Subtraction in Excess-3 Code	57
3.4.1 Addition	57
3.4.2 Subtraction	57
3.5 Binary Multiplication	58
3.5.1 Repeated Left-Shift and Add Algorithm	59
3.5.2 Repeated Add and Right-Shift Algorithm	59
3.6 Binary Division	60
3.6.1 Repeated Right-Shift and Subtract Algorithm	61
3.6.2 Repeated Subtract and Left-Shift Algorithm	62
3.7 Floating-Point Arithmetic	64
3.7.1 Addition and Subtraction	65
3.7.2 Multiplication and Division	65

Review Questions	67
Problems	68
Further Reading	68
4 Logic Gates and Related Devices	69
4.1 Positive and Negative Logic	69
4.2 Truth Table	70
4.3 Logic Gates	71
4.3.1 OR Gate	71
4.3.2 AND Gate	73
4.3.3 NOT Gate	75
4.3.4 EXCLUSIVE-OR Gate	76
4.3.5 NAND Gate	79
4.3.6 NOR Gate	79
4.3.7 EXCLUSIVE-NOR Gate	80
4.3.8 INHIBIT Gate	82
4.4 Universal Gates	85
4.5 Gates with Open Collector/Drain Outputs	85
4.6 Tristate Logic Gates	87
4.7 AND-OR-INVERT Gates	87
4.8 Schmitt Gates	88
4.9 Special Output Gates	91
4.10 Fan-Out of Logic Gates	95
4.11 Buffers and Transceivers	98
4.12 IEEE/ANSI Standard Symbols	100
4.12.1 IEEE/ANSI Standards – Salient Features	100
4.12.2 ANSI Symbols for Logic Gate ICs	101
4.13 Some Common Applications of Logic Gates	102
4.13.1 OR Gate	103
4.13.2 AND Gate	104
4.13.3 EX-OR/EX-NOR Gate	104
4.13.4 Inverter	105
4.14 Application-Relevant Information	107
Review Questions	109
Problems	110
Further Reading	114
5 Logic Families	115
5.1 Logic Families – Significance and Types	115
5.1.1 Significance	115
5.1.2 Types of Logic Family	116
5.2 Characteristic Parameters	118
5.3 Transistor Transistor Logic (TTL)	124
5.3.1 Standard TTL	125
5.3.2 Other Logic Gates in Standard TTL	127
5.3.3 Low-Power TTL	133
5.3.4 High-Power TTL (74H/54H)	134
5.3.5 Schottky TTL (74S/54S)	135

5.3.6	<i>Low-Power Schottky TTL (74LS/54LS)</i>	136
5.3.7	<i>Advanced Low-Power Schottky TTL (74ALS/54ALS)</i>	137
5.3.8	<i>Advanced Schottky TTL (74AS/54AS)</i>	139
5.3.9	<i>Fairchild Advanced Schottky TTL (74F/54F)</i>	140
5.3.10	<i>Floating and Unused Inputs</i>	141
5.3.11	<i>Current Transients and Power Supply Decoupling</i>	142
5.4	Emitter Coupled Logic (ECL)	147
5.4.1	<i>Different Subfamilies</i>	147
5.4.2	<i>Logic Gate Implementation in ECL</i>	148
5.4.3	<i>Salient Features of ECL</i>	150
5.5	CMOS Logic Family	151
5.5.1	<i>Circuit Implementation of Logic Functions</i>	151
5.5.2	<i>CMOS Subfamilies</i>	165
5.6	BiCMOS Logic	170
5.6.1	<i>BiCMOS Inverter</i>	171
5.6.2	<i>BiCMOS NAND</i>	171
5.7	NMOS and PMOS Logic	172
5.7.1	<i>PMOS Logic</i>	173
5.7.2	<i>NMOS Logic</i>	174
5.8	Integrated Injection Logic (I²L) Family	174
5.9	Comparison of Different Logic Families	176
5.10	Guidelines to Using TTL Devices	176
5.11	Guidelines to Handling and Using CMOS Devices	179
5.12	Interfacing with Different Logic Families	179
5.12.1	<i>CMOS-to-TTL Interface</i>	179
5.12.2	<i>TTL-to-CMOS Interface</i>	180
5.12.3	<i>TTL-to-ECL and ECL-to-TTL Interfaces</i>	180
5.12.4	<i>CMOS-to-ECL and ECL-to-CMOS Interfaces</i>	183
5.13	Classification of Digital ICs	183
5.14	Application-Relevant Information	184
	Review Questions	185
	Problems	185
	Further Reading	187
6	Boolean Algebra and Simplification Techniques	189
6.1	Introduction to Boolean Algebra	189
6.1.1	<i>Variables, Literals and Terms in Boolean Expressions</i>	190
6.1.2	<i>Equivalent and Complement of Boolean Expressions</i>	190
6.1.3	<i>Dual of a Boolean Expression</i>	191
6.2	Postulates of Boolean Algebra	192
6.3	Theorems of Boolean Algebra	192
6.3.1	<i>Theorem 1 (Operations with '0' and '1')</i>	192
6.3.2	<i>Theorem 2 (Operations with '0' and '1')</i>	193
6.3.3	<i>Theorem 3 (Idempotent or Identity Laws)</i>	193
6.3.4	<i>Theorem 4 (Complementation Law)</i>	193
6.3.5	<i>Theorem 5 (Commutative Laws)</i>	194
6.3.6	<i>Theorem 6 (Associative Laws)</i>	194
6.3.7	<i>Theorem 7 (Distributive Laws)</i>	195

6.3.8	<i>Theorem 8</i>	196
6.3.9	<i>Theorem 9</i>	197
6.3.10	<i>Theorem 10 (Absorption Law or Redundancy Law)</i>	197
6.3.11	<i>Theorem 11</i>	197
6.3.12	<i>Theorem 12 (Consensus Theorem)</i>	198
6.3.13	<i>Theorem 13 (DeMorgan's Theorem)</i>	199
6.3.14	<i>Theorem 14 (Transposition Theorem)</i>	200
6.3.15	<i>Theorem 15</i>	201
6.3.16	<i>Theorem 16</i>	201
6.3.17	<i>Theorem 17 (Involution Law)</i>	202
6.4	<i>Simplification Techniques</i>	204
6.4.1	<i>Sum-of-Products Boolean Expressions</i>	204
6.4.2	<i>Product-of-Sums Expressions</i>	205
6.4.3	<i>Expanded Forms of Boolean Expressions</i>	206
6.4.4	<i>Canonical Form of Boolean Expressions</i>	206
6.4.5	<i>Σ and Π Nomenclature</i>	207
6.5	<i>Quine–McCluskey Tabular Method</i>	208
6.5.1	<i>Tabular Method for Multi-Output Functions</i>	212
6.6	<i>Karnaugh Map Method</i>	216
6.6.1	<i>Construction of a Karnaugh Map</i>	216
6.6.2	<i>Karnaugh Map for Boolean Expressions with a Larger Number of Variables</i>	222
6.6.3	<i>Karnaugh Maps for Multi-Output Functions</i>	225
	<i>Review Questions</i>	230
	<i>Problems</i>	230
	<i>Further Reading</i>	231
7	Arithmetic Circuits	233
7.1	<i>Combinational Circuits</i>	233
7.2	<i>Implementing Combinational Logic</i>	235
7.3	<i>Arithmetic Circuits – Basic Building Blocks</i>	236
7.3.1	<i>Half-Adder</i>	236
7.3.2	<i>Full Adder</i>	237
7.3.3	<i>Half-Subtractor</i>	240
7.3.4	<i>Full Subtractor</i>	242
7.3.5	<i>Controlled Inverter</i>	244
7.4	<i>Adder–Subtractor</i>	245
7.5	<i>BCD Adder</i>	246
7.6	<i>Carry Propagation–Look-Ahead Carry Generator</i>	254
7.7	<i>Arithmetic Logic Unit (ALU)</i>	260
7.8	<i>Multipliers</i>	260
7.9	<i>Magnitude Comparator</i>	261
7.9.1	<i>Cascading Magnitude Comparators</i>	263
7.10	<i>Application-Relevant Information</i>	266
	<i>Review Questions</i>	266
	<i>Problems</i>	267
	<i>Further Reading</i>	268

8	Multiplexers and Demultiplexers	269
8.1	Multiplexer	269
8.1.1	<i>Inside the Multiplexer</i>	271
8.1.2	<i>Implementing Boolean Functions with Multiplexers</i>	273
8.1.3	<i>Multiplexers for Parallel-to-Serial Data Conversion</i>	277
8.1.4	<i>Cascading Multiplexer Circuits</i>	280
8.2	Encoders	280
8.2.1	<i>Priority Encoder</i>	281
8.3	Demultiplexers and Decoders	285
8.3.1	<i>Implementing Boolean Functions with Decoders</i>	286
8.3.2	<i>Cascading Decoder Circuits</i>	288
8.4	Application-Relevant Information	293
	Review Questions	294
	Problems	295
	Further Reading	298
9	Programmable Logic Devices	299
9.1	Fixed Logic Versus Programmable Logic	299
9.1.1	<i>Advantages and Disadvantages</i>	301
9.2	Programmable Logic Devices – An Overview	302
9.2.1	<i>Programmable ROMs</i>	302
9.2.2	<i>Programmable Logic Array</i>	302
9.2.3	<i>Programmable Array Logic</i>	304
9.2.4	<i>Generic Array Logic</i>	305
9.2.5	<i>Complex Programmable Logic Device</i>	306
9.2.6	<i>Field-Programmable Gate Array</i>	307
9.3	Programmable ROMs	308
9.4	Programmable Logic Array	312
9.5	Programmable Array Logic	317
9.5.1	<i>PAL Architecture</i>	319
9.5.2	<i>PAL Numbering System</i>	320
9.6	Generic Array Logic	325
9.7	Complex Programmable Logic Devices	328
9.7.1	<i>Internal Architecture</i>	328
9.7.2	<i>Applications</i>	330
9.8	Field-Programmable Gate Arrays	331
9.8.1	<i>Internal Architecture</i>	331
9.8.2	<i>Applications</i>	333
9.9	Programmable Interconnect Technologies	333
9.9.1	<i>Fuse</i>	334
9.9.2	<i>Floating-Gate Transistor Switch</i>	334
9.9.3	<i>Static RAM-Controlled Programmable Switches</i>	335
9.9.4	<i>Antifuse</i>	335
9.10	Design and Development of Programmable Logic Hardware	337
9.11	Programming Languages	338
9.11.1	<i>ABEL-Hardware Description Language</i>	339
9.11.2	<i>VHDL-VHSIC Hardware Description Language</i>	339

9.11.3	<i>Verilog</i>	339
9.11.4	<i>Java HDL</i>	340
9.12	Application Information on PLDs	340
9.12.1	<i>SPLDs</i>	340
9.12.2	<i>CPLDs</i>	343
9.12.3	<i>FPGAs</i>	349
	Review Questions	352
	Problems	353
	Further Reading	355
10	Flip-Flops and Related Devices	357
10.1	Multivibrator	357
10.1.1	<i>Bistable Multivibrator</i>	357
10.1.2	<i>Schmitt Trigger</i>	358
10.1.3	<i>Monostable Multivibrator</i>	360
10.1.4	<i>Astable Multivibrator</i>	362
10.2	Integrated Circuit (IC) Multivibrators	363
10.2.1	<i>Digital IC-Based Monostable Multivibrator</i>	363
10.2.2	<i>IC Timer-Based Multivibrators</i>	363
10.3	<i>R-S Flip-Flop</i>	373
10.3.1	<i>R-S Flip-Flop with Active LOW Inputs</i>	374
10.3.2	<i>R-S Flip-Flop with Active HIGH Inputs</i>	375
10.3.3	<i>Clocked R-S Flip-Flop</i>	377
10.4	Level-Triggered and Edge-Triggered Flip-Flops	381
10.5	<i>J-K Flip-Flop</i>	382
10.5.1	<i>J-K Flip-Flop with PRESET and CLEAR Inputs</i>	382
10.5.2	<i>Master-Slave Flip-Flops</i>	382
10.6	Toggle Flip-Flop (<i>T Flip-Flop</i>)	390
10.6.1	<i>J-K Flip-Flop as a Toggle Flip-Flop</i>	391
10.7	<i>D Flip-Flop</i>	394
10.7.1	<i>J-K Flip-Flop as D Flip-Flop</i>	395
10.7.2	<i>D Latch</i>	395
10.8	Synchronous and Asynchronous Inputs	398
10.9	Flip-Flop Timing Parameters	399
10.9.1	<i>Set-Up and Hold Times</i>	399
10.9.2	<i>Propagation Delay</i>	399
10.9.3	<i>Clock Pulse HIGH and LOW Times</i>	401
10.9.4	<i>Asynchronous Input Active Pulse Width</i>	401
10.9.5	<i>Clock Transition Times</i>	402
10.9.6	<i>Maximum Clock Frequency</i>	402
10.10	Flip-Flop Applications	402
10.10.1	<i>Switch Debouncing</i>	402
10.10.2	<i>Flip-Flop Synchronization</i>	404
10.10.3	<i>Detecting the Sequence of Edges</i>	404
10.11	Application-Relevant Data	407
	Review Questions	408
	Problems	409
	Further Reading	410

11	Counters and Registers	411
11.1	Ripple (Asynchronous) Counter	411
11.1.1	<i>Propagation Delay in Ripple Counters</i>	412
11.2	Synchronous Counter	413
11.3	Modulus of a Counter	413
11.4	Binary Ripple Counter – Operational Basics	413
11.4.1	<i>Binary Ripple Counters with a Modulus of Less than 2^N</i>	416
11.4.2	<i>Ripple Counters in IC Form</i>	418
11.5	Synchronous (or Parallel) Counters	423
11.6	UP/DOWN Counters	425
11.7	Decade and BCD Counters	426
11.8	Presetable Counters	426
11.8.1	<i>Variable Modulus with Presetable Counters</i>	428
11.9	Decoding a Counter	428
11.10	Cascading Counters	433
11.10.1	<i>Cascading Binary Counters</i>	433
11.10.2	<i>Cascading BCD Counters</i>	435
11.11	Designing Counters with Arbitrary Sequences	438
11.11.1	<i>Excitation Table of a Flip-Flop</i>	438
11.11.2	<i>State Transition Diagram</i>	439
11.11.3	<i>Design Procedure</i>	439
11.12	Shift Register	447
11.12.1	<i>Serial-In Serial-Out Shift Register</i>	449
11.12.2	<i>Serial-In Parallel-Out Shift Register</i>	452
11.12.3	<i>Parallel-In Serial-Out Shift Register</i>	452
11.12.4	<i>Parallel-In Parallel-Out Shift Register</i>	453
11.12.5	<i>Bidirectional Shift Register</i>	455
11.12.6	<i>Universal Shift Register</i>	455
11.13	Shift Register Counters	459
11.13.1	<i>Ring Counter</i>	459
11.13.2	<i>Shift Counter</i>	460
11.14	IEEE/ANSI Symbology for Registers and Counters	464
11.14.1	<i>Counters</i>	464
11.14.2	<i>Registers</i>	466
11.15	Application-Relevant Information	466
	Review Questions	466
	Problems	469
	Further Reading	471
12	Data Conversion Circuits – D/A and A/D Converters	473
12.1	Digital-to-Analogue Converters	473
12.1.1	<i>Simple Resistive Divider Network for D/A Conversion</i>	474
12.1.2	<i>Binary Ladder Network for D/A Conversion</i>	475
12.2	D/A Converter Specifications	476
12.2.1	<i>Resolution</i>	476
12.2.2	<i>Accuracy</i>	477
12.2.3	<i>Conversion Speed or Settling Time</i>	477
12.2.4	<i>Dynamic Range</i>	478

12.2.5	<i>Nonlinearity and Differential Nonlinearity</i>	478
12.2.6	<i>Monotonocity</i>	478
12.3	Types of D/A Converter	479
12.3.1	<i>Multiplying D/A Converters</i>	479
12.3.2	<i>Bipolar-Output D/A Converters</i>	480
12.3.3	<i>Companding D/A Converters</i>	480
12.4	Modes of Operation	480
12.4.1	<i>Current Steering Mode of Operation</i>	480
12.4.2	<i>Voltage Switching Mode of Operation</i>	481
12.5	BCD-Input D/A Converter	482
12.6	Integrated Circuit D/A Converters	486
12.6.1	<i>DAC-08</i>	486
12.6.2	<i>DAC-0808</i>	487
12.6.3	<i>DAC-80</i>	487
12.6.4	<i>AD 7524</i>	489
12.6.5	<i>DAC-1408/DAC-1508</i>	489
12.7	D/A Converter Applications	490
12.7.1	<i>D/A Converter as a Multiplier</i>	490
12.7.2	<i>D/A converter as a Divider</i>	490
12.7.3	<i>Programmable Integrator</i>	491
12.7.4	<i>Low-Frequency Function Generator</i>	492
12.7.5	<i>Digitally Controlled Filters</i>	493
12.8	A/D Converters	495
12.9	A/D Converter Specifications	495
12.9.1	<i>Resolution</i>	495
12.9.2	<i>Accuracy</i>	496
12.9.3	<i>Gain and Offset Errors</i>	496
12.9.4	<i>Gain and Offset Drifts</i>	496
12.9.5	<i>Sampling Frequency and Aliasing Phenomenon</i>	496
12.9.6	<i>Quantization Error</i>	496
12.9.7	<i>Nonlinearity</i>	497
12.9.8	<i>Differential Nonlinearity</i>	497
12.9.9	<i>Conversion Time</i>	498
12.9.10	<i>Aperture and Acquisition Times</i>	498
12.9.11	<i>Code Width</i>	499
12.10	A/D Converter Terminology	499
12.10.1	<i>Unipolar Mode Operation</i>	499
12.10.2	<i>Bipolar Mode Operation</i>	499
12.10.3	<i>Coding</i>	499
12.10.4	<i>Low Byte and High Byte</i>	499
12.10.5	<i>Right-Justified Data, Left-Justified Data</i>	499
12.10.6	<i>Command Register, Status Register</i>	500
12.10.7	<i>Control Lines</i>	500
12.11	Types of A/D Converter	500
12.11.1	<i>Simultaneous or Flash A/D Converters</i>	500
12.11.2	<i>Half-Flash A/D Converter</i>	503
12.11.3	<i>Counter-Type A/D Converter</i>	504
12.11.4	<i>Tracking-Type A/D Converter</i>	505

12.11.5	<i>Successive Approximation Type A/D Converter</i>	505
12.11.6	<i>Single-, Dual- and Multislope A/D Converters</i>	506
12.11.7	<i>Sigma-Delta A/D Converter</i>	509
12.12	Integrated Circuit A/D Converters	513
12.12.1	<i>ADC-0800</i>	513
12.12.2	<i>ADC-0808</i>	514
12.12.3	<i>ADC-80/AD ADC-80</i>	515
12.12.4	<i>ADC-84/ADC-85/AD ADC-84/AD ADC-85/AD-5240</i>	516
12.12.5	<i>AD 7820</i>	516
12.12.6	<i>ICL 7106/ICL 7107</i>	517
12.13	A/D Converter Applications	520
12.13.1	<i>Data Acquisition</i>	521
	Review Questions	522
	Problems	523
	Further Reading	523
13	Microprocessors	525
13.1	Introduction to Microprocessors	525
13.2	Evolution of Microprocessors	527
13.3	Inside a Microprocessor	528
13.3.1	<i>Arithmetic Logic Unit (ALU)</i>	529
13.3.2	<i>Register File</i>	529
13.3.3	<i>Control Unit</i>	531
13.4	Basic Microprocessor Instructions	531
13.4.1	<i>Data Transfer Instructions</i>	531
13.4.2	<i>Arithmetic Instructions</i>	532
13.4.3	<i>Logic Instructions</i>	533
13.4.4	<i>Control Transfer or Branch or Program Control Instructions</i>	533
13.4.5	<i>Machine Control Instructions</i>	534
13.5	Addressing Modes	534
13.5.1	<i>Absolute or Memory Direct Addressing Mode</i>	534
13.5.2	<i>Immediate Addressing Mode</i>	535
13.5.3	<i>Register Direct Addressing Mode</i>	535
13.5.4	<i>Register Indirect Addressing Mode</i>	535
13.5.5	<i>Indexed Addressing Mode</i>	536
13.5.6	<i>Implicit Addressing Mode and Relative Addressing Mode</i>	537
13.6	Microprocessor Selection	537
13.6.1	<i>Selection Criteria</i>	537
13.6.2	<i>Microprocessor Selection Table for Common Applications</i>	539
13.7	Programming Microprocessors	540
13.8	RISC Versus CISC Processors	541
13.9	Eight-Bit Microprocessors	541
13.9.1	<i>8085 Microprocessor</i>	541
13.9.2	<i>Motorola 6800 Microprocessor</i>	544
13.9.3	<i>Zilog Z80 Microprocessor</i>	546
13.10	16-Bit Microprocessors	547
13.10.1	<i>8086 Microprocessor</i>	547
13.10.2	<i>80186 Microprocessor</i>	548

13.10.3	80286 Microprocessor	548
13.10.4	MC68000 Microprocessor	549
13.11	32-Bit Microprocessors	551
13.11.1	80386 Microprocessor	551
13.11.2	MC68020 Microprocessor	553
13.11.3	MC68030 Microprocessor	554
13.11.4	80486 Microprocessor	555
13.11.5	PowerPC RISC Microprocessors	557
13.12	Pentium Series of Microprocessors	557
13.12.1	Salient Features	558
13.12.2	Pentium Pro Microprocessor	559
13.12.3	Pentium II Series	559
13.12.4	Pentium III and Pentium IV Microprocessors	559
13.12.5	Pentium M, D and Extreme Edition Processors	559
13.12.6	Celeron and Xeon Processors	560
13.13	Microprocessors for Embedded Applications	560
13.14	Peripheral Devices	560
13.14.1	Programmable Timer/Counter	561
13.14.2	Programmable Peripheral Interface	561
13.14.3	Programmable Interrupt Controller	561
13.14.4	DMA Controller	561
13.14.5	Programmable Communication Interface	562
13.14.6	Math Coprocessor	562
13.14.7	Programmable Keyboard/Display Interface	562
13.14.8	Programmable CRT Controller	562
13.14.9	Floppy Disk Controller	563
13.14.10	Clock Generator	563
13.14.11	Octal Bus Transceiver	563
	Review Questions	563
	Further Reading	564
14	Microcontrollers	565
14.1	Introduction to the Microcontroller	565
14.1.1	Applications	567
14.2	Inside the Microcontroller	567
14.2.1	Central Processing Unit (CPU)	568
14.2.2	Random Access Memory (RAM)	569
14.2.3	Read Only Memory (ROM)	569
14.2.4	Special-Function Registers	569
14.2.5	Peripheral Components	569
14.3	Microcontroller Architecture	574
14.3.1	Architecture to Access Memory	574
14.3.2	Mapping Special-Function Registers into Memory Space	576
14.3.3	Processor Architecture	577
14.4	Power-Saving Modes	579
14.5	Application-Relevant Information	580
14.5.1	Eight-Bit Microcontrollers	580
14.5.2	16-Bit Microcontrollers	588

14.5.3	32-Bit Microcontrollers	590
14.6	Interfacing Peripheral Devices with a Microcontroller	592
14.6.1	Interfacing LEDs	592
14.6.2	Interfacing Electromechanical Relays	593
14.6.3	Interfacing Keyboards	594
14.6.4	Interfacing Seven-Segment Displays	596
14.6.5	Interfacing LCD Displays	598
14.6.6	Interfacing A/D Converters	600
14.6.7	Interfacing D/A Converters	600
	Review Questions	602
	Problems	602
	Further Reading	603
15	Computer Fundamentals	605
15.1	Anatomy of a Computer	605
15.1.1	Central Processing Unit	606
15.1.2	Memory	606
15.1.3	Input/Output Ports	607
15.2	A Computer System	607
15.3	Types of Computer System	607
15.3.1	Classification of Computers on the Basis of Applications	607
15.3.2	Classification of Computers on the Basis of the Technology Used	608
15.3.3	Classification of Computers on the Basis of Size and Capacity	609
15.4	Computer Memory	610
15.4.1	Primary Memory	611
15.5	Random Access Memory	612
15.5.1	Static RAM	612
15.5.2	Dynamic RAM	619
15.5.3	RAM Applications	622
15.6	Read Only Memory	622
15.6.1	ROM Architecture	623
15.6.2	Types of ROM	624
15.6.3	Applications of ROMs	629
15.7	Expanding Memory Capacity	632
15.7.1	Word Size Expansion	632
15.7.2	Memory Location Expansion	634
15.8	Input and Output Ports	637
15.8.1	Serial Ports	638
15.8.2	Parallel Ports	640
15.8.3	Internal Buses	642
15.9	Input/Output Devices	642
15.9.1	Input Devices	643
15.9.2	Output Devices	643
15.10	Secondary Storage or Auxiliary Storage	645
15.10.1	Magnetic Storage Devices	645
15.10.2	Magneto-Optical Storage Devices	648
15.10.3	Optical Storage Devices	648
15.10.4	USB Flash Drive	650

Review Questions	650
Problems	650
Further Reading	651
16 Troubleshooting Digital Circuits and Test Equipment	653
16.1 General Troubleshooting Guidelines	653
16.1.1 <i>Faults Internal to Digital Integrated Circuits</i>	654
16.1.2 <i>Faults External to Digital Integrated Circuits</i>	655
16.2 Troubleshooting Sequential Logic Circuits	659
16.3 Troubleshooting Arithmetic Circuits	663
16.4 Troubleshooting Memory Devices	664
16.4.1 <i>Troubleshooting RAM Devices</i>	664
16.4.2 <i>Troubleshooting ROM Devices</i>	664
16.5 Test and Measuring Equipment	665
16.6 Digital Multimeter	665
16.6.1 <i>Advantages of Using a Digital Multimeter</i>	666
16.6.2 <i>Inside the Digital Meter</i>	666
16.6.3 <i>Significance of the Half-Digit</i>	666
16.7 Oscilloscope	668
16.7.1 <i>Importance of Specifications and Front-Panel Controls</i>	668
16.7.2 <i>Types of Oscilloscope</i>	669
16.8 Analogue Oscilloscopes	669
16.9 CRT Storage Type Analogue Oscilloscopes	669
16.10 Digital Oscilloscopes	669
16.11 Analogue Versus Digital Oscilloscopes	672
16.12 Oscilloscope Specifications	672
16.12.1 <i>Analogue Oscilloscopes</i>	673
16.12.2 <i>Analogue Storage Oscilloscope</i>	674
16.12.3 <i>Digital Storage Oscilloscope</i>	674
16.13 Oscilloscope Probes	677
16.13.1 <i>Probe Compensation</i>	677
16.14 Frequency Counter	678
16.14.1 <i>Universal Counters – Functional Modes</i>	679
16.14.2 <i>Basic Counter Architecture</i>	679
16.14.3 <i>Reciprocal Counters</i>	681
16.14.4 <i>Continuous-Count Counters</i>	682
16.14.5 <i>Counter Specifications</i>	682
16.14.6 <i>Microwave Counters</i>	683
16.15 Frequency Synthesizers and Synthesized Function/Signal Generators	684
16.15.1 <i>Direct Frequency Synthesis</i>	684
16.15.2 <i>Indirect Synthesis</i>	685
16.15.3 <i>Sampled Sine Synthesis (Direct Digital Synthesis)</i>	687
16.15.4 <i>Important Specifications</i>	689
16.15.5 <i>Synthesized Function Generators</i>	689
16.15.6 <i>Arbitrary Waveform Generator</i>	690
16.16 Logic Probe	691
16.17 Logic Analyser	692
16.17.1 <i>Operational Modes</i>	692

16.17.2	<i>Logic Analyser Architecture</i>	692
16.17.3	<i>Key Specifications</i>	695
16.18	Computer–Instrument Interface Standards	696
16.18.1	<i>IEEE-488 Interface</i>	696
16.19	Virtual Instrumentation	697
16.19.1	<i>Use of Virtual Instruments</i>	698
16.19.2	<i>Components of a Virtual Instrument</i>	700
	Review Questions	703
	Problems	704
	Further Reading	705
Subject Index		707

Preface

Digital electronics is essential to understanding the design and working of a wide range of applications, from consumer and industrial electronics to communications; from embedded systems, and computers to security and military equipment. As the devices used in these applications decrease in size and employ more complex technology, it is essential for engineers and students to fully understand both the fundamentals and also the implementation and application principles of digital electronics, devices and integrated circuits, thus enabling them to use the most appropriate and effective technique to suit their technical needs.

Digital Electronics: Principles, Devices and Applications is a comprehensive book covering, in one volume, both the fundamentals of digital electronics and the applications of digital devices and integrated circuits. It is different from similar books on the subject in more than one way. Each chapter in the book, whether it is related to operational fundamentals or applications, is amply illustrated with diagrams and design examples. In addition, the book covers several new topics, which are of relevance to any one having an interest in digital electronics and not covered in the books already in print on the subject. These include digital troubleshooting, digital instrumentation, programmable logic devices, microprocessors and microcontrollers. While the book covers in entirety what is required by undergraduate and graduate level students of engineering in electrical, electronics, computer science and information technology disciplines, it is intended to be a very useful reference book for professionals, R&D scientists and students at post graduate level.

The book is divided into sixteen chapters covering seven major topics. These are: *digital electronics fundamentals* (chapters 1 to 6), *combinational logic circuits* (chapters 7 and 8), *programmable logic devices* (chapter 9), *sequential logic circuits* (chapters 10 and 11), *data conversion devices and circuits* (chapter 12), *microprocessors, microcontrollers and microcomputers* (chapters 13 to 15) and *digital troubleshooting and instrumentation* (chapter 16). The contents of each of the sixteen chapters are briefly described in the following paragraphs.

The first six chapters deal with the fundamental topics of digital electronics. These include different number systems that can be used to represent data and binary codes used for representing numeric and alphanumeric data. Conversion from one number system to another and similarly conversion from one code to another is discussed at length in these chapters. Binary arithmetic, covering different methods of performing arithmetic operations on binary numbers is discussed next. Chapters four and five cover logic gates and logic families. The main topics covered in these two chapters are various logic gates and related devices, different logic families used to hardware implement digital integrated circuits, the interface between digital ICs belonging to different logic families and application information such

as guidelines for using logic devices of different families. Boolean algebra and its various postulates and theorems and minimization techniques, providing exhaustive coverage of both Karnaugh mapping and Quine-McCluskey techniques, are discussed in chapter six. The discussion includes application of these minimization techniques for multi-output Boolean functions and Boolean functions with larger number of variables. The concepts underlying different fundamental topics of digital electronics and discussed in first six chapters have been amply illustrated with solved examples.

As a follow-up to logic gates – the most basic building block of combinational logic – chapters 7 and 8 are devoted to more complex combinational logic circuits. While chapter seven covers arithmetic circuits, including different types of adders and subtractors, such as half and full adder and subtractor, adder-subtractor, larger bit adders and subtractors, multipliers, look ahead carry generator, magnitude comparator, and arithmetic logic unit, chapter eight covers multiplexers, de-multiplexers, encoders and decoders. This is followed by a detailed account of programmable logic devices in chapter nine. Simple programmable logic devices (SPLDs) such as PAL, PLA, GAL and HAL devices, complex programmable logic devices (CPLDs) and field programmable gate arrays (FPGAs) have been exhaustively treated in terms of their architecture, features and applications. Popular devices, from various international manufacturers, in the three above-mentioned categories of programmable logic devices are also covered with regard to their architecture, features and facilities.

The next two chapters, 10 and 11, cover the sequential logic circuits. Discussion begins with the most fundamental building block of sequential logic, that is, *flip flop*. Different types of flip flops are covered in detail with regard to their operational fundamentals, different varieties in each of the categories of flip flops and their applications. Multivibrator circuits, being operationally similar to flip flops, are also covered at length in this chapter. Counters and registers are the other very important building blocks of sequential logic with enormous application potential. These are covered in chapter 11. Particular emphasis is given to timing requirements and design of counters with varying count sequence requirements. The chapter also includes a detailed description of the design principles of counters with arbitrary count sequences. Different types of shift registers and some special counters that have evolved out of shift registers have been covered in detail.

Chapter 12 covers data conversion circuits including digital-to-analogue and analogue-to-digital converters. Topics covered in this chapter include operational basics, characteristic parameters, types and applications. Emphasis is given to definition and interpretation of the terminology and the performance parameters that characterize these devices. Different types of digital-to-analogue and analogue-to-digital converters, together with their merits and drawbacks are also addressed. Particular attention is given to their applications. Towards the end of the chapter, application oriented information in the form of popular type numbers along with their major performance specifications, pin connection diagrams etc. is presented. Another highlight of the chapter is the inclusion of detailed descriptions of newer types of converters, such as quad slope and sigma-delta types of analogue-to-digital converters.

Chapters 13 and 14 discuss microprocessors and microcontrollers – the two versatile devices that have revolutionized the application potential of digital devices and integrated circuits. The entire range of microprocessors and microcontrollers along with their salient features, operational aspects and application guidelines are covered in detail. As a natural follow-up to these, microcomputer fundamentals, with regard to their architecture, input/output devices and memory devices, are discussed in chapter 15.

The last chapter covers digital troubleshooting techniques and digital instrumentation. Troubleshooting guidelines for various categories of digital electronics circuits are discussed. These will particularly benefit practising engineers and electronics enthusiasts. The concepts are illustrated with the help of a large number of troubleshooting case studies pertaining to combinational, sequential and memory devices. A wide range of digital instruments is covered after a discussion on troubleshooting guidelines. The instruments covered include digital multimeters, digital oscilloscopes, logic probes,

logic analysers, frequency synthesizers, and synthesized function generators. Computer-instrument interface standards and the concept of virtual instrumentation are also discussed at length towards the end of the chapter.

As an extra resource, a companion website for my book contains lot of additional application relevant information on digital devices and integrated circuits. The information on this website includes numerical and functional indices of digital integrated circuits belonging to different logic families, pin connection diagrams and functional tables of different categories of general purpose digital integrated circuits and application relevant information on microprocessors, peripheral devices and microcontrollers. Please go to URL http://www.wiley.com/go/maini_digital.

The motivation to write this book and the selection of topics to be covered were driven mainly by the absence a book, which, in one volume, covers all the important aspects of digital technology. A large number of books in print on the subject cover all the routine topics of digital electronics in a conventional way with total disregard to the needs of application engineers and professionals. As the author, I have made an honest attempt to cover the subject in entirety by including comprehensive treatment of newer topics that are either ignored or inadequately covered in the available books on the subject of digital electronics. This is done keeping in view the changed requirements of my intended audience, which includes undergraduate and graduate level students, R&D scientists, professionals and application engineers.

Anil K. Maini

1

Number Systems

The study of *number systems* is important from the viewpoint of understanding how data are represented before they can be processed by any digital system including a digital computer. It is one of the most basic topics in digital electronics. In this chapter we will discuss different number systems commonly used to represent data. We will begin the discussion with the decimal number system. Although it is not important from the viewpoint of digital electronics, a brief outline of this will be given to explain some of the underlying concepts used in other number systems. This will then be followed by the more commonly used number systems such as the binary, octal and hexadecimal number systems.

1.1 Analogue Versus Digital

There are two basic ways of representing the numerical values of the various physical quantities with which we constantly deal in our day-to-day lives. One of the ways, referred to as *analogue*, is to express the numerical value of the quantity as a continuous range of values between the two expected extreme values. For example, the temperature of an oven settable anywhere from 0 to 100 °C may be measured to be 65 °C or 64.96 °C or 64.958 °C or even 64.9579 °C and so on, depending upon the accuracy of the measuring instrument. Similarly, voltage across a certain component in an electronic circuit may be measured as 6.5 V or 6.49 V or 6.487 V or 6.4869 V. The underlying concept in this mode of representation is that variation in the numerical value of the quantity is continuous and could have any of the infinite theoretically possible values between the two extremes.

The other possible way, referred to as *digital*, represents the numerical value of the quantity in steps of discrete values. The numerical values are mostly represented using binary numbers. For example, the temperature of the oven may be represented in steps of 1 °C as 64 °C, 65 °C, 66 °C and so on. To summarize, while an analogue representation gives a continuous output, a digital representation produces a discrete output. Analogue systems contain devices that process or work on various physical quantities represented in analogue form. Digital systems contain devices that process the physical quantities represented in digital form.

Digital techniques and systems have the advantages of being relatively much easier to design and having higher accuracy, programmability, noise immunity, easier storage of data and ease of fabrication in integrated circuit form, leading to availability of more complex functions in a smaller size. The real world, however, is analogue. Most physical quantities – position, velocity, acceleration, force, pressure, temperature and flowrate, for example – are analogue in nature. That is why analogue variables representing these quantities need to be digitized or discretized at the input if we want to benefit from the features and facilities that come with the use of digital techniques. In a typical system dealing with analogue inputs and outputs, analogue variables are digitized at the input with the help of an analogue-to-digital converter block and reconverted back to analogue form at the output using a digital-to-analogue converter block. Analogue-to-digital and digital-to-analogue converter circuits are discussed at length in the latter part of the book. In the following sections we will discuss various number systems commonly used for digital representation of data.

1.2 Introduction to Number Systems

We will begin our discussion on various number systems by briefly describing the parameters that are common to all number systems. An understanding of these parameters and their relevance to number systems is fundamental to the understanding of how various systems operate. Different characteristics that define a number system include the number of independent digits used in the number system, the place values of the different digits constituting the number and the maximum numbers that can be written with the given number of digits. Among the three characteristic parameters, the most fundamental is the number of independent digits or symbols used in the number system. It is known as the *radix* or *base* of the number system. The decimal number system with which we are all so familiar can be said to have a radix of 10 as it has 10 independent digits, i.e. 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9. Similarly, the binary number system with only two independent digits, 0 and 1, is a radix-2 number system. The octal and hexadecimal number systems have a radix (or base) of 8 and 16 respectively. We will see in the following sections that the radix of the number system also determines the other two characteristics. The place values of different digits in the integer part of the number are given by r^0 , r^1 , r^2 , r^3 and so on, starting with the digit adjacent to the radix point. For the fractional part, these are r^{-1} , r^{-2} , r^{-3} and so on, again starting with the digit next to the radix point. Here, r is the radix of the number system. Also, maximum numbers that can be written with n digits in a given number system are equal to r^n .

1.3 Decimal Number System

The decimal number system is a radix-10 number system and therefore has 10 different digits or symbols. These are 0, 1, 2, 3, 4, 5, 6, 7, 8 and 9. All higher numbers after '9' are represented in terms of these 10 digits only. The process of writing higher-order numbers after '9' consists in writing the second digit (i.e. '1') first, followed by the other digits, one by one, to obtain the next 10 numbers from '10' to '19'. The next 10 numbers from '20' to '29' are obtained by writing the third digit (i.e. '2') first, followed by digits '0' to '9', one by one. The process continues until we have exhausted all possible two-digit combinations and reached '99'. Then we begin with three-digit combinations. The first three-digit number consists of the lowest two-digit number followed by '0' (i.e. 100), and the process goes on endlessly.

The place values of different digits in a mixed decimal number, starting from the decimal point, are 10^0 , 10^1 , 10^2 and so on (for the integer part) and 10^{-1} , 10^{-2} , 10^{-3} and so on (for the fractional part).

The value or magnitude of a given decimal number can be expressed as the sum of the various digits multiplied by their place values or weights.

As an illustration, in the case of the decimal number 3586.265, the integer part (i.e. 3586) can be expressed as

$$3586 = 6 \times 10^0 + 8 \times 10^1 + 5 \times 10^2 + 3 \times 10^3 = 6 + 80 + 500 + 3000 = 3586$$

and the fractional part can be expressed as

$$265 = 2 \times 10^{-1} + 6 \times 10^{-2} + 5 \times 10^{-3} = 0.2 + 0.06 + 0.005 = 0.265$$

We have seen that the place values are a function of the radix of the concerned number system and the position of the digits. We will also discover in subsequent sections that the concept of each digit having a place value depending upon the position of the digit and the radix of the number system is equally valid for the other more relevant number systems.

1.4 Binary Number System

The binary number system is a radix-2 number system with '0' and '1' as the two independent digits. All larger binary numbers are represented in terms of '0' and '1'. The procedure for writing higher-order binary numbers after '1' is similar to the one explained in the case of the decimal number system. For example, the first 16 numbers in the binary number system would be 0, 1, 10, 11, 100, 101, 110, 111, 1000, 1001, 1010, 1011, 1100, 1101, 1110 and 1111. The next number after 1111 is 10000, which is the lowest binary number with five digits. This also proves the point made earlier that a maximum of only 16 ($= 2^4$) numbers could be written with four digits. Starting from the binary point, the place values of different digits in a mixed binary number are 2^0 , 2^1 , 2^2 and so on (for the integer part) and 2^{-1} , 2^{-2} , 2^{-3} and so on (for the fractional part).

Example 1.1

Consider an arbitrary number system with the independent digits as 0, 1 and X. What is the radix of this number system? List the first 10 numbers in this number system.

Solution

- The radix of the proposed number system is 3.
- The first 10 numbers in this number system would be 0, 1, X, 10, 11, 1X, X0, X1, XX and 100.

1.4.1 Advantages

Logic operations are the backbone of any digital computer, although solving a problem on computer could involve an arithmetic operation too. The introduction of the mathematics of logic by George Boole laid the foundation for the modern digital computer. He reduced the mathematics of logic to a binary notation of '0' and '1'. As the mathematics of logic was well established and had proved itself to be quite useful in solving all kinds of logical problem, and also as the mathematics of logic (also known as Boolean algebra) had been reduced to a binary notation, the binary number system had a clear edge over other number systems for use in computer systems.

Yet another significant advantage of this number system was that all kinds of data could be conveniently represented in terms of 0s and 1s. Also, basic electronic devices used for hardware implementation could be conveniently and efficiently operated in two distinctly different modes. For example, a bipolar transistor could be operated either in cut-off or in saturation very efficiently.

Lastly, the circuits required for performing arithmetic operations such as addition, subtraction, multiplication, division, etc., become a simple affair when the data involved are represented in the form of 0s and 1s.

1.5 Octal Number System

The octal number system has a radix of 8 and therefore has eight distinct digits. All higher-order numbers are expressed as a combination of these on the same pattern as the one followed in the case of the binary and decimal number systems described in Sections 1.3 and 1.4. The independent digits are 0, 1, 2, 3, 4, 5, 6 and 7. The next 10 numbers that follow '7', for example, would be 10, 11, 12, 13, 14, 15, 16, 17, 20 and 21. In fact, if we omit all the numbers containing the digits 8 or 9, or both, from the decimal number system, we end up with an octal number system. The place values for the different digits in the octal number system are 8^0 , 8^1 , 8^2 and so on (for the integer part) and 8^{-1} , 8^{-2} , 8^{-3} and so on (for the fractional part).

1.6 Hexadecimal Number System

The hexadecimal number system is a radix-16 number system and its 16 basic digits are 0, 1, 2, 3, 4, 5, 6, 7, 8, 9, A, B, C, D, E and F. The place values or weights of different digits in a mixed hexadecimal number are 16^0 , 16^1 , 16^2 and so on (for the integer part) and 16^{-1} , 16^{-2} , 16^{-3} and so on (for the fractional part). The decimal equivalent of A, B, C, D, E and F are 10, 11, 12, 13, 14 and 15 respectively, for obvious reasons.

The hexadecimal number system provides a condensed way of representing large binary numbers stored and processed inside the computer. One such example is in representing addresses of different memory locations. Let us assume that a machine has 64K of memory. Such a memory has 64K ($= 2^{16} = 65\,536$) memory locations and needs 65 536 different addresses. These addresses can be designated as 0 to 65 535 in the decimal number system and 00000000 00000000 to 11111111 11111111 in the binary number system. The decimal number system is not used in computers and the binary notation here appears too cumbersome and inconvenient to handle. In the hexadecimal number system, 65 536 different addresses can be expressed with four digits from 0000 to FFFF. Similarly, the contents of the memory when represented in hexadecimal form are very convenient to handle.

1.7 Number Systems – Some Common Terms

In this section we will describe some commonly used terms with reference to different number systems.

1.7.1 Binary Number System

Bit is an abbreviation of the term 'binary digit' and is the smallest unit of information. It is either '0' or '1'. A *byte* is a string of eight bits. The byte is the basic unit of data operated upon as a single unit in computers. A *computer word* is again a string of bits whose size, called the 'word length' or 'word size', is fixed for a specified computer, although it may vary from computer to computer. The word length may equal one byte, two bytes, four bytes or be even larger.