THE ART OF ELECTRONICS

PAUL HOROWITZ
WINFIELD HILL

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THE ART OF ELECTRONICS

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TO CAROL, JACOB, MISHA, AND GINGER

CONTENTS

List of tables xvi

Preface xix

Preface to first edition xxi

CHAPTER 1
FOUNDATIONS 1

Introduction 1

Voltage, current, and resistance 2

1.01 Voltage and current 2
1.02 Relationship between voltage and current: resistors 4
1.03 Voltage dividers 8
1.04 Voltage and current sources 9
1.05 Thévenin's equivalent circuit 11
1.06 Small-signal resistance 13

Signals 15

1.07 Sinusoidal signals 15
1.08 Signal amplitudes and decibels 16
1.09 Other signals 17
1.10 Logic levels 19
1.11 Signal sources 19

Capacitors and ac circuits 20

1.12 Capacitors 20
1.13 *RC* circuits: *V* and *I* versus time 23
1.14 Differentiators 25
1.15 Integrators 26

Inductors and transformers 28

1.16 Inductors 28
1.17 Transformers 28

Impedance and reactance 29

1.18 Frequency analysis of reactive circuits 30
1.19 *RC* filters 35
1.20 Phasor diagrams 39
1.21 "Poles" and decibels per octave 40
1.22 Resonant circuits and active filters 41
1.23 Other capacitor applications 42
1.24 Thévenin's theorem generalized 44

Diodes and diode circuits 44

1.25 Diodes 44
1.26 Rectification 44
1.27 Power-supply filtering 45
1.28 Rectifier configurations for power supplies 46
1.29 Regulators 48
1.30 Circuit applications of diodes 48
1.31 Inductive loads and diode protection 52

Other passive components 53

1.32 Electromechanical devices 53
1.33 Indicators 57
1.34 Variable components 57
Additional exercises 58

CHAPTER 2
TRANSISTORS 61

Introduction 61

2.01 First transistor model: current amplifier 62

Some basic transistor circuits 63

2.02 Transistor switch 63
2.03 Emitter follower 65

Microchip Ex. 1103, p. 6
Microchip v. Aptiv
IPR2024-00228

2.04 Emitter followers as voltage regulators 68
2.05 Emitter follower biasing 69
2.06 Transistor current source 72
2.07 Common-emitter amplifier 76
2.08 Unity-gain phase splitter 77
2.09 Transconductance 78

Ebers-Moll model applied to basic transistor circuits 79

2.10 Improved transistor model: transconductance amplifier 79
2.11 The emitter follower revisited 81
2.12 The common-emitter amplifier revisited 82
2.13 Biasing the common-emitter amplifier 84
2.14 Current mirrors 88

Some amplifier building blocks 91

2.15 Push-pull output stages 91
2.16 Darlington connection 94
2.17 Bootstrapping 96
2.18 Differential amplifiers 98
2.19 Capacitance and Miller effect 102
2.20 Field-effect transistors 104

Some typical transistor circuits 104

2.21 Regulated power supply 104
2.22 Temperature controller 105
2.23 Simple logic with transistors and diodes 107

Self-explanatory circuits 107

2.24 Good circuits 107
2.25 Bad circuits 107
Additional exercises 107

CHAPTER 3
FIELD-EFFECT TRANSISTORS 113

Introduction 113

3.01 FET characteristics 114
3.02 FET types 117
3.03 Universal FET characteristics 119
3.04 FET drain characteristics 121
3.05 Manufacturing spread of FET characteristics 122

Basic FET circuits 124

3.06 JFET current sources 125
3.07 FET amplifiers 129
3.08 Source followers 133
3.09 FET gate current 135
3.10 FETs as variable resistors 138

FET switches 140

3.11 FET analog switches 141
3.12 Limitations of FET switches 144
3.13 Some FET analog switch examples 151
3.14 MOSFET logic and power switches 153
3.15 MOSFET handling precautions 169

Self-explanatory circuits 171

3.16 Circuit ideas 171
3.17 Bad circuits 171 vskip6pt

CHAPTER 4
FEEDBACK AND OPERATIONAL AMPLIFIERS 175

Introduction 175

4.01 Introduction to feedback 175
4.02 Operational amplifiers 176
4.03 The golden rules 177

Basic op-amp circuits 177

4.04 Inverting amplifier 177
4.05 Noninverting amplifier 178
4.06 Follower 179
4.07 Current sources 180
4.08 Basic cautions for op-amp circuits 182

An op-amp smorgasbord 183

4.09 Linear circuits 183
4.10 Nonlinear circuits 187

A detailed look at op-amp behavior 188

4.11 Departure from ideal op-amp performance 189
4.12 Effects of op-amp limitations on circuit behavior 193
4.13 Low-power and programmable op-amps 210

Microchip Ex. 1103, p. 7
Microchip v. Aptiv
IPR2024-00228

A detailed look at selected op-amp circuits 213

4.14 Logarithmic amplifier 213
4.15 Active peak detector 217
4.16 Sample-and-hold 220
4.17 Active clamp 221
4.18 Absolute-value circuit 221
4.19 Integrators 222
4.20 Differentiators 224

Op-amp operation with a single power supply 224

4.21 Biasing single-supply ac amplifiers 225
4.22 Single-supply op-amps 225

Comparators and Schmitt trigger 229

4.23 Comparators 229
4.24 Schmitt trigger 231

Feedback with finite-gain amplifiers 232

4.25 Gain equation 232
4.26 Effects of feedback on amplifier circuits 233
4.27 Two examples of transistor amplifiers with feedback 236

Some typical op-amp circuits 238

4.28 General-purpose lab amplifier 238
4.29 Voltage-controlled oscillator 240
4.30 JFET linear switch with R_{ON} compensation 241
4.31 TTL zero-crossing detector 242
4.32 Load-current-sensing circuit 242

Feedback amplifier frequency compensation 242

4.33 Gain and phase shift versus frequency 243
4.34 Amplifier compensation methods 245
4.35 Frequency response of the feedback network 247

Self-explanatory circuits 250

4.36 Circuit ideas 250
4.37 Bad circuits 250
Additional exercises 251

CHAPTER 5
ACTIVE FILTERS AND OSCILLATORS 263

Active filters 263

5.01 Frequency response with *RC* filters 263
5.02 Ideal performance with *LC* filters 265
5.03 Enter active filters: an overview 266
5.04 Key filter performance criteria 267
5.05 Filter types 268

Active filter circuits 272

5.06 VCVS circuits 273
5.07 VCVS filter design using our simplified table 274
5.08 State-variable filters 276
5.09 Twin-T notch filters 279
5.10 Gyrator filter realizations 281
5.11 Switched-capacitor filters 281

Oscillators 284

5.12 Introduction to oscillators 284
5.13 Relaxation oscillators 284
5.14 The classic timer chip: the 555 286
5.15 Voltage-controlled oscillators 291
5.16 Quadrature oscillators 291
5.17 Wien bridge and *LC* oscillators 296
5.18 *LC* oscillators 297
5.19 Quartz-crystal oscillators 300

Self-explanatory circuits 303

5.20 Circuit ideas 303
Additional exercises 303

CHAPTER 6
VOLTAGE REGULATORS AND POWER CIRCUITS 307

Basic regulator circuits with the classic 723 307

Microchip Ex. 1103, p. 8
Microchip v. Aptiv
IPR2024-00228

6.01 The 723 regulator 307
6.02 Positive regulator 309
6.03 High-current regulator 311

Heat and power design 312

6.04 Power transistors and heat sinking 312
6.05 Foldback current limiting 316
6.06 Overvoltage crowbars 317
6.07 Further considerations in high-current power-supply design 320
6.08 Programmable supplies 321
6.09 Power-supply circuit example 323
6.10 Other regulator ICs 325

The unregulated supply 325

6.11 ac line components 326
6.12 Transformer 328
6.13 dc components 329

Voltage references 331

6.14 Zener diodes 332
6.15 Bandgap (V_{BE}) reference 335

Three-terminal and four-terminal regulators 341

6.16 Three-terminal regulators 341
6.17 Three-terminal adjustable regulators 344
6.18 Additional comments about 3-terminal regulators 345
6.19 Switching regulators and dc-dc converters 355

Special-purpose power-supply circuits 368

6.20 High-voltage regulators 368
6.21 Low-noise, low-drift supplies 374
6.22 Micropower regulators 376
6.23 Flying-capacitor (charge pump) voltage converters 377
6.24 Constant-current supplies 379
6.25 Commercial power-supply modules 382

Self-explanatory circuits 384

6.26 Circuit ideas 384
6.27 Bad circuits 384
Additional exercises 384

CHAPTER 7
PRECISION CIRCUITS AND LOW-NOISE TECHNIQUES 391

Precision op-amp design techniques 391

7.01 Precision versus dynamic range 391
7.02 Error budget 392
7.03 Example circuit: precision amplifier with automatic null offset 392
7.04 A precision-design error budget 394
7.05 Component errors 395
7.06 Amplifier input errors 396
7.07 Amplifier output errors 403
7.08 Auto-zeroing (chopper-stabilized) amplifiers 415

Differential and instrumentation amplifiers 421

7.09 Differencing amplifier 421
7.10 Standard three-op-amp instrumentation amplifier 425

Amplifier noise 428

7.11 Origins and kinds of noise 430
7.12 Signal-to-noise ratio and noise figure 433
7.13 Transistor amplifier voltage and current noise 436
7.14 Low-noise design with transistors 438
7.15 FET noise 443
7.16 Selecting low-noise transistors 445
7.17 Noise in differential and feedback amplifiers 445

Noise measurements and noise sources 449

7.18 Measurement without a noise source 449
7.19 Measurement with noise source 450
7.20 Noise and signal sources 452
7.21 Bandwidth limiting and rms voltage measurement 453
7.22 Noise potpourri 454

Microchip Ex. 1103, p. 9
Microchip v. Aptiv
IPR2024-00228

Interference: shielding and grounding 455

7.23 Interference 455
7.24 Signal grounds 457
7.25 Grounding between instruments 457

Self-explanatory circuits 466

7.26 Circuit ideas 466
Additional exercises 466

CHAPTER 8
DIGITAL ELECTRONICS 471

Basic logic concepts 471

8.01 Digital versus analog 471
8.02 Logic states 472
8.03 Number codes 473
8.04 Gates and truth tables 478
8.05 Discrete circuits for gates 480
8.06 Gate circuit example 481
8.07 Assertion-level logic notation 482

TTL and CMOS 484

8.08 Catalog of common gates 484
8.09 IC gate circuits 485
8.10 TTL and CMOS characteristics 486
8.11 Three-state and open-collector devices 487

Combinational logic 490

8.12 Logic identities 491
8.13 Minimization and Karnaugh maps 492
8.14 Combinational functions available as ICs 493
8.15 Implementing arbitrary truth tables 500

Sequential logic 504

8.16 Devices with memory: flip-flops 504
8.17 Clocked flip-flops 507
8.18 Combining memory and gates: sequential logic 512
8.19 Synchronizer 515

Monostable multivibrators 517

8.20 One-shot characteristics 517
8.21 Monostable circuit example 519
8.22 Cautionary notes about monostables 519
8.23 Timing with counters 522

Sequential functions available as ICs 523

8.24 Latches and registers 523
8.25 Counters 524
8.26 Shift registers 525
8.27 Sequential PALs 527
8.28 Miscellaneous sequential functions 541

Some typical digital circuits 544

8.29 Modulo-*n* counter: a timing example 544
8.30 Multiplexed LED digital display 546
8.31 Sidereal telescope drive 548
8.32 An *n*-pulse generator 548

Logic pathology 551

8.33 dc problems 551
8.34 Switching problems 552
8.35 Congenital weaknesses of TTL and CMOS 554

Self-explanatory circuits 556

8.36 Circuit ideas 556
8.37 Bad circuits 556
Additional exercises 556

CHAPTER 9
DIGITAL MEETS ANALOG 565

CMOS and TTL logic interfacing 565

9.01 Logic family chronology 565
9.02 Input and output characteristics 570
9.03 Interfacing between logic families 572
9.04 Driving CMOS amd TTL inputs 575
9.05 Driving digital logic from comparators and op-amps 577

Microchip Ex. 1103, p. 10
Microchip v. Aptiv
IPR2024-00228

9.06 Some comments about logic inputs 579
9.07 Comparators 580
9.08 Driving external digital loads from CMOS and TTL 582
9.09 NMOS LSI interfacing 588
9.10 Opto-electronics 590

Digital signals and long wires 599

9.11 On-board interconnections 599
9.12 Intercard connections 601
9.13 Data buses 602
9.14 Driving cables 603

Analog/digital conversion 612

9.15 Introduction to A/D conversion 612
9.16 Digital-to-analog converters (DACs) 614
9.17 Time-domain (averaging) DACs 618
9.18 Multiplying DACs 619
9.19 Choosing a DAC 619
9.20 Analog-to-digital converters 621
9.21 Charge-balancing techniques 626
9.22 Some unusual A/D and D/A converters 630
9.23 Choosing an ADC 631

Some A/D conversion examples 636

9.24 16-Channel A/D data-acquisition system 636
9.25 $3\frac{1}{2}$-Digit voltmeter 638
9.26 Coulomb meter 640

Phase-locked loops 641

9.27 Introduction to phase-locked loops 641
9.28 PLL design 646
9.29 Design example: frequency multiplier 647
9.30 PLL capture and lock 651
9.31 Some PLL applications 652

Pseudo-random bit sequences and noise generation 655

9.32 Digital noise generation 655
9.33 Feedback shift register sequences 655
9.34 Analog noise generation from maximal-length sequences 658
9.35 Power spectrum of shift register sequences 658
9.36 Low-pass filtering 660
9.37 Wrap-up 661
9.38 Digital filters 664

Self-explanatory circuits 667

9.39 Circuit ideas 667
9.40 Bad circuits 668
Additional exercises 668

CHAPTER 10
MICROCOMPUTERS 673

Minicomputers, microcomputers, and microprocessors 673

10.01 Computer architecture 674

A computer instruction set 678

10.02 Assembly language and machine language 678
10.03 Simplified 8086/8 instruction set 679
10.04 A programming example 683

Bus signals and interfacing 684

10.05 Fundamental bus signals: data, address, strobe 684
10.06 Programmed I/O: data out 685
10.07 Programmed I/O: data in 689
10.08 Programmed I/O: status registers 690
10.09 Interrupts 693
10.10 Interrupt handling 695
10.11 Interrupts in general 697
10.12 Direct memory access 701
10.13 Summary of the IBM PC's bus signals 704
10.14 Synchronous versus asynchronous bus communication 707
10.15 Other microcomputer buses 708
10.16 Connecting peripherals to the computer 711

Microchip Ex. 1103, p. 11
Microchip v. Aptiv
IPR2024-00228

Software system concepts 714

10.17 Programming 714
10.18 Operating systems, files, and use of memory 716

Data communications concepts 719

10.19 Serial communication and ASCII 720
10.20 Parallel communication: Centronics, SCSI, IPI, GPIB (488) 730
10.21 Local area networks 734
10.22 Interface example: hardware data packing 736
10.23 Number formats 738

CHAPTER 11
MICROPROCESSORS 743

A detailed look at the 68008 744

11.01 Registers, memory, and I/O 744
11.02 Instruction set and addressing 745
11.03 Machine-language representation 750
11.04 Bus signals 753

A complete design example: analog signal averager 760

11.05 Circuit design 760
11.06 Programming: defining the task 774
11.07 Programming: details 777
11.08 Performance 796
11.09 Some afterthoughts 797

Microprocessor support chips 799

11.10 Medium-scale integration 800
11.11 Peripheral LSI chips 802
11.12 Memory 812
11.13 Other microprocessors 820
11.14 Emulators, development systems, logic analyzers, and evaluation boards 821

CHAPTER 12
ELECTRONIC CONSTRUCTION TECHNIQUES 827

Prototyping methods 827

12.01 Breadboards 827
12.02 PC prototyping boards 828
12.03 Wire-Wrap panels 828

Printed circuits 830

12.04 PC board fabrication 830
12.05 PC board design 835
12.06 Stuffing PC boards 838
12.07 Some further thoughts on PC boards 840
12.08 Advanced techniques 841

Instrument construction 852

12.09 Housing circuit boards in an instrument 852
12.10 Cabinets 854
12.11 Construction hints 855
12.12 Cooling 855
12.13 Some electrical hints 858
12.14 Where to get components 860

CHAPTER 13
HIGH-FREQUENCY AND HIGH-SPEED TECHNIQUES 863

High-frequency amplifiers 863

13.01 Transistor amplifiers at high frequencies: first look 863
13.02 High-frequency amplifiers: the ac model 864
13.03 A high-frequency calculation example 866
13.04 High-frequency amplifier configurations 868
13.05 A wideband design example 869
13.06 Some refinements to the ac model 872
13.07 The shunt-series pair 872
13.08 Modular amplifiers 873

Radiofrequency circuit elements 879

13.09 Transmission lines 879

Microchip Ex. 1103, p. 12
Microchip v. Aptiv
IPR2024-00228

13.10 Stubs, baluns, and transformers 881
13.11 Tuned amplifiers 882
13.12 Radiofrequency circuit elements 884
13.13 Measuring amplitude or power 888

Radiofrequency communications: AM 892

13.14 Some communications concepts 892
13.15 Amplitude modulation 894
13.16 Superheterodyne receiver 895

Advanced modulation methods 897

13.17 Single sideband 897
13.18 Frequency modulation 898
13.19 Frequency-shift keying 900
13.20 Pulse-modulation schemes 900

Radiofrequency circuit tricks 902

13.21 Special construction techniques 902
13.22 Exotic RF amplifiers and devices 903

High-speed switching 904

13.23 Transistor model and equations 905
13.24 Analog modeling tools 908

Some switching-speed examples 909

13.25 High-voltage driver 909
13.26 Open-collector bus driver 910
13.27 Example: photomultiplier preamp 911

Self-explanatory circuits 913

13.28 Circuit ideas 913
Additional exercises 913

CHAPTER 14
LOW-POWER DESIGN 917

Introduction 917

14.01 Low-power applications 918

Power sources 920

14.02 Battery types 920
14.03 Wall-plug-in units 931
14.04 Solar cells 932
14.05 Signal currents 933

Power switching and micropower regulators 938

14.06 Power switching 938
14.07 Micropower regulators 941
14.08 Ground reference 944
14.09 Micropower voltage references and temperature sensors 948

Linear micropower design techniques 948

14.10 Problems of micropower linear design 950
14.11 Discrete linear design example 950
14.12 Micropower operational amplifiers 951
14.13 Micropower comparators 965
14.14 Micropower timers and oscillators 965

Micropower digital design 969

14.15 CMOS families 969
14.16 Keeping CMOS low power 970
14.17 Micropower microprocessors and peripherals 974
14.18 Microprocessor design example: degree-day logger 978

Self-explanatory circuits 985

14.19 Circuit ideas 985

CHAPTER 15
MEASUREMENTS AND SIGNAL PROCESSING 987

Overview 987

Measurement transducers 988

15.01 Temperature 988
15.02 Light level 996
15.03 Strain and displacement 1001

Microchip Ex. 1103, p. 13
Microchip v. Aptiv
IPR2024-00228

15.04 Acceleration, pressure, force, velocity 1004
15.05 Magnetic field 1007
15.06 Vacuum gauges 1007
15.07 Particle detectors 1008
15.08 Biological and chemical voltage probes 1012

Precision standards and precision measurements 1016

15.09 Frequency standards 1016
15.10 Frequency, period, and time-interval measurements 1019
15.11 Voltage and resistance standards and measurements 1025

Bandwidth-narrowing techniques 1026

15.12 The problem of signal-to-noise ratio 1026
15.13 Signal averaging and multichannel averaging 1026
15.14 Making a signal periodic 1030
15.15 Lock-in detection 1031
15.16 Pulse-height analysis 1034
15.17 Time-to-amplitude converters 1035

Spectrum analysis and Fourier transforms 1035

15.18 Spectrum analyzers 1035
15.19 Off-line spectrum analysis 1038

Self-explanatory circuits 1038

15.20 Circuit ideas 1038

APPENDIXES 1043

Appendix A
The oscilloscope 1045

Appendix B
Math review 1050

Appendix C
The 5% resistor color code 1053

Appendix D
1% Precision resistors 1054

Appendix E
How to draw schematic diagrams 1056

Appendix F
Load lines 1059

Appendix G
Transistor saturation 1062

Appendix H
***LC* Butterworth filters 1064**

Appendix I
Electronics magazines and journals 1068

Appendix J
IC prefixes 1069

Appendix K
Data sheets 1072

2N4400-1 NPN transistor 1073
LF411-12 JFET operational amplifier 1078
LM317 3-terminal adjustable regulator 1086

Bibliography 1095

Index 1101

Microchip Ex. 1103, p. 14
Microchip v. Aptiv
IPR2024-00228

TABLES

1.1 Diodes 43
2.1 Small-signal transistors 109
3.1 JFETs 125
3.2 MOSFETs 126
3.3 Dual matched JFETs 128
3.4 Current regulator diodes 129
3.5 Power MOSFETs 164
3.6 BJT-MOSFET comparison 166
3.7 Electrostatic voltages 170
4.1 Operational amplifiers 196
4.2 Recommended op-amps 208
4.3 High-voltage op-amps 213
4.4 Power op-amps 214
5.1 Time-domain filter comparison 273
5.2 VCVS low-pass filters 274
5.3 555-type oscillators 289
5.4 Selected VCOs 293
6.1 Power transistors 314
6.2 Transient suppressors 326
6.3 Power-line filters 327
6.4 Rectifiers 331
6.5 Zener and reference diodes 334
6.6 500mW zeners 334
6.7 IC voltage references 336
6.8 Fixed voltage regulators 342
6.9 Adjustable voltage regulators 346
6.10 Dual-tracking regulators 352
7.1 Seven precision op-amps 401
7.2 Precision op-amps 404
7.3 High-speed precision op-amps 412
7.4 Fast buffers 418
7.5 Instrumentation amplifiers 429
8.1 4-bit integers 477
8.2 TTL and CMOS gates 484
8.3 Logic identities 491
8.4 Buffers 560
8.5 Transceivers 560
8.6 Decoders 561
8.7 Magnitude comparators 561
8.8 Monostable multivibrators 562
8.9 D-registers and latches 562
8.10 Counters 563
8.11 Shift registers 564
9.1 Logic family characteristics 570
9.2 Allowed connections between logic families 574
9.3 Comparators 584
9.4 D/A converters 620
9.5 A/D converters 632
9.6 Integrating A/D converters 634
10.1 IBM PC bus 704
10.2 Computer buses 709
10.3 ASCII codes 721
10.4 RS-232 signals 724
10.5 Serial data standards 727
10.6 Centronics (printer) signals 730
11.1 68000/8 instruction set 746
11.2 Allowable addressing modes 748
11.3 68000/8 addressing modes 749
11.4 68008 bus signals 753
11.5 68000/8 vectors 788
11.6 Zilog 8530 registers 804
11.7 Zilog 8530 serial port initialization 806
11.8 Microprocessors 822
12.1 PC graphic patterns 839
12.2 Venturi fans 858
13.1 RF transistors 877
13.2 Wideband op-amps 878
14.1 Primary batteries 922
14.2 Battery characteristics 923
14.3 Primary-battery attributes 930

Microchip Ex. 1103, p. 15
Microchip v. Aptiv
IPR2024-00228

14.4 Low-power regulators 942
14.5 Micropower voltage references 949
14.6 Micropower op-amps 956
14.7 Programmable op-amps 958
14.8 Low-power comparators 966
14.9 Microprocessor controllers 976
14.10 Temperature logger current drain 983
15.1 Thermocouples 990
D.1 Selected resistor types 1055
H.1 Butterworth low-pass filters 1064

Microchip Ex. 1103, p. 16
Microchip v. Aptiv
IPR2024-00228

```
**  Expanded Product Terms **

D0 =>
    a & b & c & d & !e & g
  # a & b & c & !e & f & g
  # a & c & d & !e & f & g
  # b & c & !d & !e & !f & !g
  # !a & !b & c & d & e & f & g
  # a & !b & !c & !d & e & f & g
  # !a & b & c & d & e & !f & g

D1 =>
    a & !b & !c & e & f & g
  # !b & c & d & e & f & g
  # a & b & c & !d & e & f & g
  # a & b & !c & d & e & !f & g
  # a & b & c & d & !e & !f & g
  # a & b & c & !d & !e & !f & !g

D2 =>
    a & !b & !c & d & e & f
  # a & !b & c & d & f & g
  # a & !b & !c & e & f & g
  # !a & b & c & !d & !e & f & g
  # !a & b & c & d & e & !f & g
  # !a & !b & !c & d & e & !f & g
  # a & b & c & !d & !e & !f & !g

D3 =>
    a & b & c & f & g
  # a & !b & !c & d & e & f
  # a & !b & !c & e & f & g
  # !a & !b & c & d & e & f & g
  # !a & b & c & d & e & !f & g
  # !a & !b & !c & d & e & !f & g

D0.oe  => 1
D1.oe  => 1
D2.oe  => 1
D3.oe  => 1
```

Figure 8.78. 7-segment-to-hex encoder: minimized product terms.

CUPL example: vending machine (sequential). An arbitrary state machine (Section 8.18) has a set of *states* and a set of *transition rules* for moving between those states at each clock edge. In general, the transition rules depend both on the present state and on the particular combination of input levels present at the next clock edge. You can implement a state machine in programmable logic containing registers if (a) there are enough register bits to represent all possible states (e.g., with 4 registers you could have up to 16 states) and (b) there are enough inputs and logic gates to implement the transition rules.

As an example, let's design a registered PAL for the state diagram of Figure 8.80. It's a vending machine, and it is supposed to disgorge a bottle of fizzy sweet liquid when 25 cents (or more) has been deposited. There is some sort of coin interface that gobbles up and recognizes money and sends to our PAL a 2-bit input (C1, C0), valid for one clock edge, indicating the coin just deposited (01 = nickel, 10 = dime, 11 = quarter, 00 = slug or no coin).

Microchip Ex. 1103, p. 17
Microchip v. Aptiv
IPR2024-00228

```
** Fuse Plot **

Pin #19
 0000 --------------------------------
 0032 x-x-x-----------x---x-----------
 0064 -xx--x--x---x---x---------------
 0096 -xx--x------x---x---x-----------
 0128 -x-xx---x---x---x---x-----------
 0160 x--xx---x---x----x--x-----------
 0192 -x-x-x--x---x----x--x-----------
 0224 xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

Pin #18
 0256 --------------------------------
 0288 -xx--x--x---x---x---------------
 0320 -xx-x---x-------x---x-----------
 0352 -xx--x------x---x---x-----------
 0384 x--xx----x---x--x---x-----------
 0416 x--xx---x---x----x--x-----------
 0448 -x-x-x--x---x----x--x-----------
 0480 x-x-x----x---x---x---x----------

Pin #17
 0512 --------------------------------
 0544 -xx--x------x---x---x-----------
 0576 -x--x---x---x---x---x-----------
 0608 x-x-x----x--x---x---x-----------
 0640 x-x--x--x---x----x--x-----------
 0672 x-x-x---x----x---x--x-----------
 0704 x-x-x----x---x---x---x----------
 0736 xxxxxxxxxxxxxxxxxxxxxxxxxxxxxxxx

Pin #16
 0768 --------------------------------
 0800 x-x-x---x----x------x-----------
 0832 x-x-x--------x--x---x-----------
 0864 --x-x---x----x--x---x-----------
 0896 x---x----x---x---x---x----------
 0928 -x-xx---x---x---x---x-----------
 0960 -xx--x---x--x---x---x-----------
 0992 x--xx---x---x----x--x-----------

LEGEND     X : fuse not blown
           - : fuse blown
```

Figure 8.79. 7-segment-to-hex encoder: fuse map.

The state machine's job is to add up the total deposited and generate an output called *bottle* when there's enough money.

Figure 8.81 shows the specification, in CUPL's state-machine syntax. As before, we begin by defining input and output pins. Note that we've added a *reset* input so that you can initialize to the state S0 (no money). Next we define the states, then the rules for moving between them. If any outputs, either registered or combinational, need to be generated during states or transitions between states, they are specified at the same time. In this example, for instance, the output *bottle* has been specified as a separate output register, so that no output state decoding is needed. In fact, this is the only output needed, and the state-machine bits Q0–2 could by implemented in internal registers that don't generate outputs directly; some programmable logic devices have such

Microchip Ex. 1103, p. 18
Microchip v. Aptiv
IPR2024-00228

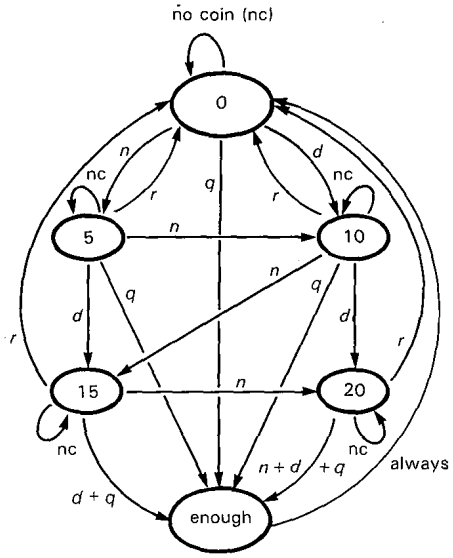

Figure 8.80. Vending machine state diagram.

"buried" registers, in addition to the usual output registers.

Note that you have to specify explicitly the transition from a state to itself, as we have done here for the input *nocoin*. An unspecified condition implicitly resets the state to all zeros. That is because these conditionals are compiled into combinational logic to assert the D inputs of the registers, and thus if the condition is not met, the corresponding D input is not asserted.

Figure 8.82 shows the output from CUPL. There is nothing obvious or simple about the logic, because both the machine state (S0–S5) and the input variable (C0–1) are specified as binary numbers, whereas the logic operates on individual

```
/**  Inputs  **/

Pin  1  = clk    ;  /* clock -- positive edge  */
Pin  3  = c0     ;  /* coin type -- low bit    */
Pin  4  = c1     ;  /* coin type -- high bit   */
Pin  6  = reset  ;  /* reset input             */


/**  Outputs  **/

Pin  18  = !Q0     ;  /* bit 0 of state variable   */
Pin  17  = !Q1     ;  /* bit 1                     */
Pin  16  = !Q2     ;  /* bit 2                     */
Pin  15  = !bottle ;  /* bottle disgorge command   */

/* Define machine states with symbolic names;
      "enough" = 25 cents or more */

$define S0     'b'000
$define S5     'b'001
$define S10    'b'010
$define S15    'b'011
$define S20    'b'100
$define ENOUGH 'b'101

/* define intermediate variables */

nocoin = !c0 & !c1 & !reset;
nickel =  c0 & !c1 & !reset;
dime =   !c0 &  c1 & !reset;
quarter = c0 &  c1 & !reset;

/* Define state bit variable field */

field statebit = [Q2..0] ;
```

Figure 8.81. Vending machine specification (CUPL). (*Continued on next page.*)

Microchip Ex. 1103, p. 19
Microchip v. Aptiv
IPR2024-00228

```
/* Transition rules for vending machine */

sequence statebit {
   present S0    if nocoin     next S0;
                 if nickel     next S5;
                 if dime       next S10;
                 if quarter    next ENOUGH   out bottle;

   present S5    if nocoin     next S5;
                 if nickel     next S10;
                 if dime       next S15;
                 if quarter    next ENOUGH   out bottle;

   present S10   if nocoin     next S10;
                 if nickel     next S15;
                 if dime       next S20;
                 if quarter    next ENOUGH   out bottle;

   present S15   if nocoin     next S15;
                 if nickel     next S20;
                 if dime       next ENOUGH   out bottle;
                 if quarter    next ENOUGH   out bottle;

   present S20   if nocoin     next S20;
                 if nickel     next ENOUGH   out bottle;
                 if dime       next ENOUGH   out bottle;
                 if quarter    next ENOUGH   out bottle;

   present ENOUGH              next S0;    }
```

Figure 8.81. (*cont.*)

bits. Thus, the resulting logic does not bear much relation to the original state description (Fig. 8.81). In fact, the particular choice of states (ascending binary, 0–5) could have been chosen differently, completely changing the resulting logic. In this case, this example fits easily within the constraints of the 16R6 PAL (8 product terms per register); if it had not, we could have tried redefining the states, which often leads to a simpler logic realization. Note that the *reset* input acts by an overriding disassertion of all D inputs, which we forced by our definition of the intermediate variables *nocoin*, *nickel*, etc.

EXERCISE 8.30

Verify that the finished logic equations are correct, by checking a few transition rules. You might try all the transitions from 00, or a nickel or dime from some other state.

EXERCISE 8.31

Good vending machines give change. Redraw the state diagram (Fig. 8.80) so that there are states (how many?) for each possible amount of change. Modify the transition rules accordingly. Make sure your modified vending machine still does its primary job – dispensing bottles.

EXERCISE 8.32

Draw a state diagram and transition rules for an electronic combination lock: It should open only if four digits are entered in the correct order. Any error should reset it.

Hints for using programmable logic devices (PLDs)

For certain jobs, PLDs really hit the spot. Here are the most important uses and advantages of PLDs:

Microchip Ex. 1103, p. 20
Microchip v. Aptiv
IPR2024-00228