## Table of Contents

CHAPTER 1. SEE A PROGRAM RUNNING ..... 1
1.1 Translating C to Machine Code .....  1
1.2 Loading a Machine Program into Memory ..... 4
1.2.1 Harvard versus Von Neumann Architecture ..... 4
1.2.2 Creating Runtime Memory Image ..... 6
1.3 REGISTERS ..... 10
1.3.1 Reusing Registers to Improve Performance ..... 10
1.3.2 Processor Registers. ..... 12
1.4 EXECUTING A MACHINE PROGRAM ..... 15
1.4.1 Loading a Program ..... 16
1.4.2 Starting the Execution ..... 17
1.4.3 Program Completion ..... 20
1.5 SELF-REVIEW EXERCISES ..... 21
1.6 EXERCISES ..... 24
CHAPTER 2. DATA REPRESENTATION ..... 25
2.1 Bit, Byte, and Word. ..... 25
2.2 BINARY, OCTAL, DECIMAL, AND HEXADECIMAL ..... 27
2.3 UNSIGNED INTEGERS ..... 28
2.4 SIGNED INTEGERS ..... 29
2.4.1 Sign-and-Magnitude. ..... 31
2.4.2 One's Complement ..... 32
2.4.3 Two's Complement. ..... 33
2.4.4 Carry Flag for Unsigned Addition and Subtraction ..... 35
2.4.5 Overflow Flag for Signed Addition and Subtraction ..... 37
2.5 CHARACTER STRING. ..... 46
2.6 SELF-REVIEW EXERCISES ..... 48
2.7 EXERCISES ..... 49
CHAPTER 3. ARM INSTRUCTION SET ARCHITECTURE ..... 51
3.1 Instruction Set Architecture (ISA) ..... 51
3.2 ARM Instruction Set Architecture ..... 52
3.3 ARM CORTEX-M ORGANIZATION ..... 55
3.4 GOING FROM C TO ASSEMBLY ..... 57
3.5 ASSEMBLY INSTRUCTION FORMAT. ..... 60
3.6 ANATOMY OF AN AssEmbly Program ..... 62
3.7 ASSEMBLER DIRECTIVES ..... 65
3.8 SELF-REVIEW EXERCISES ..... 69
3.9 EXERCISES ..... 71
CHAPTER 4. ARITHMETIC AND LOGIC INSTRUCTIONS ..... 73
4.1 PROGRAM Status Register ..... 73
4.2 Updating Program Status Flags. ..... 75
4.3 Shift and Rotate ..... 76
4.4 ARITHMETICINSTRUCTIONS ..... 78
4.4.1 Addition and Subtraction. ..... 79
4.4.2 Short Multiplication and Division. ..... 80
4.4.3 Long Multiplication ..... 80
4.4.4 Saturation ..... 81
4.5 IMPLEMENTING A BARRELSHIFTER ..... 82
4.6 BITWISE LOGIC OPERATIONS. ..... 83
4.7 REVERSING THE ORDER OF BITS AND ByTES. ..... 87
4.8 Sign and Zero Extension ..... 89
4.9 TEST AND COMPARISON ..... 90
4.10 DATA MOVEMENT BETWEEN REGISTERS ..... 91
4.11 Bit Field Extract. ..... 92
4.12 SELF-REVIEW EXERCISES. ..... 92
4.13 EXERCISES ..... 95
CHAPTER 5. LOAD, STORE, AND STACK ..... 97
5.1 LOADING CONSTANT INTO REGISTERS ..... 97
5.1.1 Data Movement Instruction MOV and MVN. ..... 97
5.1.2 Pseudo Instruction $L D R$ and $A D R$ ..... 98
5.1.3 Comparing LDR, ADR, and MOV ..... 99
5.2 BIG AND LITTLE ENDIAN ..... 99
5.3 ACCESSING DATA IN MEMORY ..... 100
5.4 MEMORY ADDRESSING ..... 101
5.4.1 Pre-index, Post-index, and Pre-index with Update. ..... 101
5.4.2 Load and Store Instructions ..... 103
5.4.3 PC-relative Addressing. ..... 103
5.4.4 Example of Accessing an Array. ..... 104
5.5 LOADING AND STORING MULTIPLEREGISTERS. ..... 105
5.6 ACCESSING Stack MEMORY. ..... 107
5.6.1 Stack Types ..... 107
5.6.2 PUSH and POP Operations. ..... 108
5.6.3 Implementing Stacks with STM and LDM ..... 109
5.7 SELF-REVIEW EXERCISES. ..... 111
5.8 EXERCISES ..... 113
CHAPTER 6. BRANCH AND CONDITIONAL EXECUTION. ..... 117
6.1 CONDITION TESTING ..... 117
6.2 BRANCH INSTRUCTIONS ..... 119
6.3 CONDITIONALEXECUTION ..... 122
6.4 If Statement ..... 123
6.5 IF-ELSESTATEMENT. ..... 126
6.6 FOR LOOP ..... 127
6.7 WHiLE LOOP ..... 128
6.8 DO WHILE LOOP. ..... 129
6.9 CONTINUE Statement. ..... 130
6.10 BREAKSTATEMENT. ..... 131
6.11 SWITCH STATEMENT ..... 132
6.12 SELF-REVIEW EXERCISES ..... 134
6.13 EXERCISES ..... 137
CHAPTER 7. STRUCTURED PROGRAMMING ..... 141
7.1 BASIC CONTROLSTRUCTURES ..... 141
7.2 STEPWISE REFINEMENT ..... 143
7.3 REGISTER ALLOCATION ..... 146
7.4 EXAMPLE: FACTORIAL NUMBERS ..... 149
7.5 EXAMPLE: COUNTING ONES IN A WORD ..... 150
7.6 EXAMPLE: Finding the Maximum Value in an Array ..... 152
7.7 EXAMPLE: COUNTING DIGITS. ..... 154
7.8 EXAMPLE: PARITY BIT ..... 155
7.9 EXAMPLE: PERFECT NUMBERS ..... 157
7.10 EXAMPLE: ARMSTRONG NUMBERS ..... 159
7.11 EXAMPLE: PALINDROMESTRING ..... 160
7.12 EXAMPLE: CONVERTING STRING TO Integer (ATOI) ..... 162
7.13 EXAMPLE: BINARY SEARCH. ..... 163
7.14 EXAMPLE: BUBBLE SORT ..... 165
7.15 SELF-REVIEW EXERCISES ..... 167
7.16 EXERCISES ..... 168
CHAPTER 8. SUBROUTINES ..... 171
8.1 CALLING A SUBROUTINE. ..... 172
8.2 Preserving Caller's Runtime Environment via tack ..... 173
8.3 Passing Arguments to Subroutine via Registers. ..... 176
8.4 PASS-BY-VALUE AND PASS-BY-REFERENCE ..... 177
8.4.1 Example of Passing by Value: Sum of an Array ..... 179
8.4.2 Example of Passing by Reference: Swap two characters ..... 181
8.5 CALLING SUBROUTINES IN A DIFFERENT FILE ..... 182
8.6 EXAMPLE: GREATEST COMMON DIVISOR ..... 183
8.7 EXAMPLE: CONCATENATING Two STRINGS ..... 185
8.8 EXAMPLE: COMPARING Two STRINGS ..... 186
8.9 EXAMPLE: InSERTING AN INTEGER INTO A SORTED ARRAY ..... 187
8.10 EXAMPLE: CONVERTING INTEGER TO STRING (ITOA) ..... 188
8.11 EXAMPLE: MATRIX TRANSPOSE ..... 190
8.12 EXAMPLE: REMOVING A CHARACTER FROM A STRING ..... 192
8.12.1 Example: Reversing a String ..... 193
8.13 Example: Finding Unique Numbers in an Array ..... 194
8.14 PASSING ARGUMENTS THROUGHSTACK. ..... 198
8.15 RECURSIVE FUNCTIONS. ..... 200
8.15.1 Example: Factorial Numbers. ..... 202
8.15.2 Example: String Permutation ..... 203
8.15.3 Tail Recursion. ..... 205
8.16 SELF-REVIEW EXERCISES ..... 207
8.17 EXERCISES ..... 210
CHAPTER 9. 64-BIT DATA PROCESSING ..... 213
9.1 64-BIT ADDITION ..... 213
9.2 64-BIT SUBTRACTION ..... 214
9.3 64-Bit Counting Leading Zeros ..... 215
9.4 64-BIT SIGN EXTENSION ..... 215
9.5 64-BIT LOGICAL SHIFT LEFT. ..... 216
9.6 64-BIT LOGICAL SHIFT RIGHT ..... 217
9.7 64-BIT MULTIPLICATION ..... 218
9.8 64-BIT UNSIGNED DIVISION. ..... 219
9.9 64-BIT SIGNED DIVISION ..... 221
9.10 SELF-REVIEW EXERCISES. ..... 223
9.11 EXERCISES ..... 225
CHAPTER 10. MIXING C AND ASSEMBLY CODE ..... 227
10.1 DATA TYPES AND ACCESS ..... 227
10.1.1 Signed or Unsigned Integers ..... 228
10.1.2 Data Alignment ..... 229
10.1.3 Data Structure Padding. ..... 230
10.2 Special Variables ..... 233
10.2.1 Static Variables ..... 233
10.2.2 Volatile Variables. ..... 237
10.3 INLINE ASSEMBLY ..... 239
10.3.1 Assembly Functions in a C Program ..... 239
10.3.2 Inline Assembly Instructions in a C Program ..... 240
10.4 CALLING ASSEMBLY SUBROUTINES FROM A C PROGRAM ..... 241
10.4.1 Example of Calling an Assembly Subroutine ..... 241
10.4.2 Example of Accessing C Variables in Assembly. ..... 242
10.5 CALLING C Functions from Assembly Programs, ..... 243
10.5.1 Example of Calling a C Function. ..... 243
10.5.2 Example of Accessing Assembly Data in a C Program ..... 244
10.6 SELF-REVIEW EXERCISES. ..... 245
10.7 EXERCISES ..... 246
CHAPTER 11. INTERRUPTS ..... 249
11.1 InTRODUCTION TO INTERRUPTS ..... 249
11.2 INTERRUPTNUMBERS ..... 250
11.3 Interrupt Service Routines ..... 252
11.4 Interrupt Vector Table. ..... 253
11.5 Interrupt Stacking and Unstacking ..... 255
11.6 NESTED VECTORED INTERRUPT CONTROLLER (NVIC) ..... 257
11.6.1 Enable and Disable Peripheral Interrupts ..... 258
11.6.2 Interrupt Priority ..... 260
11.6.3 Global Interrupt Enable and Disable. ..... 264
11.7 SYSTEM TIMER ..... 265
11.7.1 Timer Diagram and Registers ..... 266
11.7.2 Timer Resolution and Period. ..... 268
11.7.3 Implementing a Delay Function ..... 269
11.8 EXTERNAL INTERRUPT ..... 272
11.9 SOFTWARE INTERRUPT ..... 275
11.10 SELF-REVIEW EXERCISES ..... 276
11.11 EXERCISES ..... 279
CHAPTER 12. FIXED-POINT ARITHMETIC ..... 281
12.1 FIXED-POINT REPRESENTATION ..... 282
12.1.1 Unsigned Fixed-point Representation ..... 283
12.1.2 Signed Fixed-point Representation ..... 284
12.1.3 Converting to Fixed-point Format. ..... 285
12.2 Fixed-point Range and Resolution Tradeoff. ..... 286
12.3 FIXED-POINT AdDITION AND SUBTRACTION ..... 287
12.4 FIXED-POINT MULTIPLICATION. ..... 289
12.5 FIXED-POINT DIVISION ..... 290
12.6 SELF-REVIEW EXERCISES ..... 291
12.7 EXERCISES ..... 292
CHAPTER 13. FLOATING-POINT ARITHMETIC ..... 293
13.1 FLOATING-POINT REPRESENTATION. ..... 293
13.1.1 Special Values ..... 297
13.1.2 Subnormal Numbers. ..... 297
13.1.3 Overflow and Underflow ..... 298
13.1.4 Tradeoff between Numeric Range and Resolution ..... 299
13.1.5 Rounding Rules. ..... 301
13.2 SOFTWARE-BASED FLOATING-POINT OPERATIONS. ..... 303
13.2.1 Floating-point Addition ..... 304
13.2.2 Floating-point Multiplication. ..... 308
13.3 HARDWARE-BASED FLOATING-POINT OPERATIONS. ..... 310
13.3.1 FPU Registers. ..... 311
13.3.2 Load and Store Floating-point Numbers ..... 319
13.3.3 Copy Floating-point Numbers ..... 320
13.3.4 Copy and Set the Status and Control Register. ..... 320
13.3.5 Single-precision Arithmetic Operations. ..... 321
13.3.6 Single-precision comparisons. ..... 322
13.3.7 Precision Conversion ..... 323
13.3.8 FPU Exception and Exception handling ..... 325
13.3.9 Example Assembly Programs. ..... 328
13.4 SELF-REVIEW EXERCISES ..... 330
13.5 EXERCISES ..... 334
CHAPTER 14. INSTRUCTION ENCODING AND DECODING ..... 337
14.1 TRADEOFF BETWEEN CODE DENSITY AND PERFORMANCE. ..... 337
14.2 Dividing Bit Streams into 16- or 32-bit Instructions. ..... 338
14.3 EnCODING16-BIT THUMB InSTRUCTIONS ..... 339
14.4 ENCODING 32-BIT INSTRUCTIONS ..... 340
14.5 ENCODING IMMEDIATE NUMBERS ..... 342
14.6 CALCULATING TARGET MEMORY ADDRESS ..... 343
14.7 Instruction Decoding Example 1 ..... 344
14.8 Instruction Decoding Example 2 ..... 349
14.9 SELF-REVIEW EXERCISES. ..... 353
14.10 EXERCISES ..... 354
CHAPTER 15. GENERAL PURPOSE I/O (GPIO) ..... 355
15.1 Introduction to General Purpose I/O (GPIO) ..... 355
15.2 GPIO Input Modes: Pull Up and Pull Down. ..... 356
15.3 GPIO InPUT: SCHMITT TRIGGER ..... 357
15.4 GPIO OUTPUT MODES: PUSH-PULL AND Open-DRaIN ..... 359
15.4.1 Push-Pull Output ..... 359
15.4.2 Open-Drain Output ..... 360
15.5 GPIO OUTPUT SPEED: SLEW RATE ..... 362
15.6 MEMORY-MAPPED I/O ..... 363
15.7 LIGHTING UP AN LED ..... 366
15.8 PUSH BUTTON. ..... 371
15.9 KEYPADSCAN ..... 376
15.10 STEPPER MOTOR CONTROL ..... 382
15.10.1 Bipolar and Unipolar Stepper Motor ..... 382
15.10.2 Step Angle ..... 383
15.10.3 Wave Stepping. ..... 384
15.10.4 Full Stepping. ..... 385
15.10.5 Half Stepping. ..... 386
15.10.6 Micro-stepping ..... 388
15.10.7 Driving Stepper Motor. ..... 390
15.11 LCD ..... 391
15.11.1 External Connection Diagram ..... 391
15.11.2 Internal Font Encoding. ..... 394
15.11.3 Sending Commands and Data to LCD. ..... 395
15.11.4 Programming Fonts ..... 398
15.12 SELF-REVIEW EXERCISES. ..... 399
15.13 EXERCISES ..... 402
CHAPTER 16. GENERAL-PURPOSE TIMERS ..... 405
16.1 Timer Organization and Counting Modes, ..... 405
16.2 OUTPUT COMPARE. ..... 408
16.2.1 Setting Output Mode. ..... 409
16.2.2 Example of Using a Timer to Toggle LED ..... 411
16.2.3 Timer Update Events. ..... 414
16.3 PWM OUTPUT ..... 416
16.3.1 PWM Alignment ..... 420
16.3.2 PWM Programming Flowchart ..... 421
16.4 INPUT CAPTURE ..... 425
16.4.1 Configuring Input Capture ..... 429
16.4.2 Input Capture in Slave Mode with Reset ..... 434
16.4.3 Interfacing to Ultrasonic Distance Sensor ..... 436
16.5 REAL-TIME CLOCK. ..... 442
16.5.1 UNIX Epoch Time ..... 442
16.5.2 RTC Frequency Settings ..... 444
16.5.3 Oscillator Frequency Accuracy ..... 445
16.5.4 Binary Coded Decimal (BCD) Encoding ..... 446
16.5.5 RTC Initialization ..... 447
16.5.6 RTC Alarm ..... 451
16.5.7 Using RTC to Wake Processors up from Sleep Mode. ..... 453
16.6 SELF-REVIEW EXERCISES ..... 456
16.7 EXERCISES ..... 459
CHAPTER 17. DIRECT MEMORY ACCESS (DMA) ..... 461
17.1 ADVANCED MICROCONTROLLER BUS ARCHITECTURE (AMBA) ..... 462
17.2 INTERFACING A PERIPHERAL WITHOUT AND WITH DMA ..... 464
17.3 DMA CHANNELS ..... 465
17.4 PROGRAMMING DMA ..... 468
17.5 DMA CIRCULAR MODE ..... 470
17.6 DMA INTERRUPTS ..... 471
17.7 SELF-REVIEW EXERCISES ..... 472
17.8 EXERCISES ..... 474
CHAPTER 18. ANALOG INPUT AND OUTPUT ..... 475
18.1 ANALOG-TO-DIGITALCONVERTER (ADC) ..... 475
18.1.1 ADC Architecture ..... 475
18.1.2 Digital Quantization ..... 476
18.1.3 Sample and Hold ..... 477
18.1.4 ADC Quantization Error ..... 478
18.1.5 ADC Diagram ..... 480
18.1.6 ADC Conversion Modes ..... 481
18.1.7 ADC Data Alignment ..... 483
18.1.8 ADC Input Channels ..... 484
18.1.9 ADC Triggers ..... 485
18.1.10 Measuring the Input Voltage ..... 488
18.1.11 ADC Configuration Flowchart ..... 489
18.1.12 $\quad A D C$ with $D M A$ ..... 493
18.1.13 DMA with Ping-Pong Buffering ..... 495
18.1.14 ADC Calibration ..... 497
18.2 DIGITAL-TO-ANALOG CONVERTER (DAC) ..... 498
18.2.1 DAC Architecture ..... 498
18.2.2 DAC on STM32L Processors ..... 500
18.2.3 Conversion Trigger ..... 501
18.2.4 Buffered Output ..... 501
18.2.5 Generating a Sine Wave via Table Lookup ..... 502
18.2.6 DAC with Software Trigger ..... 506
18.2.7 Using Timer as a Trigger to DAC ..... 507
18.2.8 Musical Synthesizing. ..... 510
18.3 SELF-REVIEW EXERCISES. ..... 515
18.4 EXERCISES ..... 518
CHAPTER 19. SERIAL COMMUNICATION PROTOCOLS ..... 521
19.1 UnIVERSAL ASYNCHRONOUS RECEIVER AND TRANSMITTER ..... 521
19.1.1 Communication Frame ..... 522
19.1.2 Bit Rate and Baud Rate ..... 523
19.1.3 UART Standards ..... 525
19.1.4 UART Communication via Polling ..... 526
19.1.5 UART Communication via Interrupt ..... 530
19.1.6 UART Communication via DMA ..... 533
19.1.7 Serial Communication to Bluetooth Module. ..... 536
19.2 INTER-INTEGRATED CIRCUIT ( $\mathrm{I}^{2} \mathrm{C}$ ) ..... 539
19.2.1 $\quad I^{2} C$ Pins ..... 539
19.2.2 $\quad I^{2} C$ Protocol ..... 540
19.2.3 $\quad I^{2} C$ Data Frame ..... 542
19.2.4 Interfacing Serial Digital Thermal Sensors via $I^{2} C$ ..... 543
19.2.5 $\quad I^{2}$ C Programmable Timings. ..... 545
19.2.6 Sending Data to $I^{2} C$ Slave via Polling ..... 551
19.2.7 Receiving Data from $1^{2} C$ Slave via Polling ..... 552
19.2.8 Interfacing a Temperature Sensor via Polling. ..... 553
19.2.9 Transferring Data via DMA on $I^{2} C$ Master. ..... 558
19.3 SERIAL PERIPHERAL INTERFACE BUS (SPI) ..... 560
19.3.1 Data Exchange. ..... 560
19.3.2 Clock Configuration. ..... 562
19.3.3 Using SPI to Interface a Gyroscope ..... 563
19.4 Universal Serial Bus (USB) ..... 569
19.4.1 USB Bus Layer ..... 570
19.4.2 USB Device Layer ..... 572
19.4.3 USB Function Layer ..... 574
19.4.4 USB Class Layer. ..... 582
19.4.5 Human Interface Device (HID) ..... 582
19.5 SELF-REVIEW EXERCISES. ..... 587
19.6 EXERCISES ..... 589
CHAPTER 20. MULTITASKING. ..... 591
20.1 Processor Mode and Privilege Level ..... 592
20.1.1 Control Register ..... 593
20.1.2 Exception Return Value (EXC_RETURN). ..... 594
20.1.3 Selection of MSP and PSP in Thread Mode ..... 596
20.2 SUPERVISOR CALL (SVC) ..... 597
20.3 CPU SChEDULING ..... 600
20.4 EXAMPLE OF Round Robin Scheduling ..... 602
20.5 SELF-REVIEW EXERCISES ..... 608
20.6 EXERCISES ..... 610
CHAPTER 21. DIGITAL SIGNAL PROCESSING (DSP) ..... 611
21.1 FIXED-POINT AND FLOATING-POINT DSP ..... 611
21.2 FIXED-POINT DATA TYPES IN DSP. ..... 612
21.3 SATURATION. ..... 613
21.4 ARITHMETICINSTRUCTIONS. ..... 615
21.4.1 Parallel 8-bit Add and Subtract ..... 616
21.4.2 Parallel 16-bit Add and Subtract. ..... 620
21.4.3 32-bit Add and Subtract. ..... 622
21.4.4 Sum of Absolute Difference. ..... 623
21.4.5 Extension and Add. ..... 624
21.4.6 Add and Subtract Half-words with Exchange. ..... 625
21.4.7 $\quad$ 16-bit and 32-bit Multiplication. ..... 627
21.4.8 16-bit Multiply and Accumulate with 64-bit Result. ..... 630
21.4.9 16-bit Multiply and Accumulate with 32-bit Result ..... 633
21.4.10 $16 \times 32$ Multiply and Accumulate with 32 -bit Result. ..... 635
21.4.11 $32 \times 32$ Multiply and Accumulate with 32 -bit Result ..... 635
21.4.12 Unsigned Long Multiply with Accumulate Accumulate ..... 635
21.5 Packing Half-words into a Word ..... 637
21.6 SIGNED AND UNSIGNED EXTENSION. ..... 638
21.7 GE FLAGS ..... 639
21.8 BYTE SELECTION INSTRUCTION ..... 640
21.9 BASIC DSP FUNCTIONS. ..... 641
21.9.1 Vector Negate. ..... 641
21.9.2 Vector Absolution Value ..... 642
21.9.3 Vector Offset with Saturation. ..... 644
21.9.4 Vector Shift Left with Saturation ..... 645
21.9.5 Vector Mean. ..... 647
21.9.6 Vector Pairwise Multiplication ..... 648
21.9.7 Vector Dot Product ..... 650
21.9.8 Vector Min and Max ..... 652
21.10 Self-REVIEW EXERCISES ..... 653
21.11 EXERCISES ..... 654
APPENDIX A: ASCII CHARACTERS ..... 656
APPENDIX B: GNU COMPILER ..... 657
APPENDIX C: CORTEX-M3/M4 INSTRUCTIONS ..... 668
APPENDIX D: FLOATING-POINT INSTRUCTIONS ..... 670
APPENDIX E: DSP INSTRUCTIONS ON CORTEX-M4 AND CORTEX-M7 ..... 672
APPENDIX F: CORTEX-M0/M0+/M1 INSTRUCTIONS ..... 675
APPENDIX G: CORTEX-M3/M4 16-BIT THUMB-2 INSTRUCTION ENCODING ..... 677
APPENDIX H: CORTEX-M3/M4 32-BIT THUMB-2 INSTRUCTION ENCODING. ..... 679
APPENDIX I: GPIO ALTERNATE FUNCTIONS FOR STM32L4 ..... 686
BIBLIOGRAPHY ..... 693
INDEX ..... 699
SOLUTIONS TO SELF-REVIEW EXERCISES ..... 713

