

# Digital Design Using Digilent FPGA Boards

## -- Verilog / Active-HDL Edition

### Table of Contents

<b>1. Introduction to Digital Logic</b>	1
1.1 Background	1
1.2 Digital Logic	5
1.3 Verilog	8
<b>2. Basic Logic Gates</b>	9
2.1 Truth Tables and Logic Equations	9
The Three Basic Gates	9
Four New Gates	11
2.2 Positive and Negative Logic: De Morgan's Theorem	13
2.3 Sum of Products Design	16
2.4 Product of Sums Design	15
Verilog Examples	18
Example 1 – 2-Input Gates	18
Example 2 – Multiple-Input Gates	21
Problems	24
<b>3. Boolean Algebra and Logic Equations</b>	28
3.1 Boolean Theorems	28
One-Variable Theorems	29
Two- and Three-Variable Theorems	29
3.2 Karnaugh Maps	34
Two-Variable K-Maps	34
Three-Variable K-Maps	36
Four-Variable K-Maps	38
3.3 Computer Minimization Techniques	40
Tabular Representations	40
Prime Implicants	41
Essential Prime Implicants	43
Verilog Examples	45
Example 3 – Majority Circuit	45
Example 4 – 2-Bit Comparator	47
Problems	50
<b>4. Implementing Digital Circuits</b>	52
4.1 Implementing Gates	52
4.2 Transistor-Transistor Logic (TTL)	54
4.3 Programmable Logic Devices (PLDs and CPLDs)	56
A 2-Input, 1-Output PLD	56

The GAL 16V8	58
CPLDs	60
4.4 Field Programmable Gate Arrays (FPGAs)	60
Verilog Examples	62
Example 5 – Map Report	62
Problems	63
<b>5. Combinational Logic</b>	<b>64</b>
5.1 Multiplexers	64
2-to-1 Multiplexer	64
4-to-1 Multiplexer	65
Quad 2-to-1 Multiplexer	66
Verilog Examples	67
Example 6 – 2-to-1 Multiplexer: <i>if</i> Statement	67
Example 7 – 4-to-1 Multiplexer: Module Instantiation	70
Example 8 – 4-to-1 Multiplexer: <i>case</i> Statement	74
Example 9 – A Quad 2-to-1 Multiplexer	75
Example 10 – Generic Multiplexer: Parameters	77
Example 11 – Glitches	79
5.2 7-Segment Displays	82
Verilog Examples	83
Example 12 – 7-Segment Decoder: Logic Equations	83
Example 13 – 7-Segment Decoder: <i>case</i> Statement	85
Example 14 – Multiplexing 7-Segment Displays	87
Example 15 – 7-Segment Displays: <i>x7seg</i> and <i>x7segb</i>	89
5.3 Comparators	94
Cascading Comparators	94
TTL Comparators	95
Verilog Examples	96
Example 16 – 4-Bit Comparator Using a Verilog Task	96
Example 17 – <i>N</i> -Bit Comparator Using Relational Operators	98
5.4 Decoders and Encoders	100
Decoders	100
TTL Decoders	101
Encoders	101
Priority Encoders	102
TTL Encoders	102
Verilog Examples	103
Example 18 – 3-to-8 Decoder: Logic Equations	103
Example 19 – 3-to-8 Decoder: <i>for</i> Loops	104
Example 20 – 8-to-3 Encoder: Logic Equations	105
Example 21 – 8-to-3 Encoder: <i>for</i> Loops	107
Example 22 – 8-to-3 Priority Encoder	107
5.5. Code Converters	109
Binary-to-BCD Converters	109
Shift and Add 3 Algorithm	110
Gray Code Converters	111
Verilog Examples	112
Example 23 – 4-Bit Binary-to-BCD Converter: Logic Equations	112

Example 24 – 8-Bit Binary-to-BCD Converter: <i>for</i> Loops	113
Example 25 – 4-Bit Binary to Gray Code Converter	115
Example 26 – 4-Bit Gray Code to Binary Converter	116
Problems	117
<b>6. Arithmetic Circuits</b>	<b>120</b>
6.1 Adders	120
Half Adder	120
Full Adder	120
Carry and Overflow	123
TTL Adder	125
Verilog Examples	125
Example 27 – 4-Bit Adder: Logic Equations	125
Example 28 – 4-Bit Adder: Behavioral Statements	128
Example 29 – <i>N</i> -Bit Adder: Behavioral Statements	129
6.2 Subtractors	129
Half Subtractor	129
Full Subtractor	130
An Adder/Subtractor Circuit	131
Verilog Examples	133
Example 30 – 4-Bit Adder/Subtractor: Logic Equations	133
Example 31 – <i>N</i> -Bit Subtractor: Behavioral Statements	134
6.3 Shifters	135
Verilog Examples	136
Example 32 – 4-Bit Shifter	136
6.4 Multiplication	137
Binary Multiplication	137
Signed Multiplication	139
Verilog Examples	140
Example 33 – Multiplying by a Constant	140
Example 34 – A 4-Bit Multiplier	141
6.5 Division	143
Binary Division	143
Verilog Examples	144
Example 35 – An 8-Bit Divider using a Task	144
6.6 Arithmetic Logic Unit (ALU)	146
Verilog Examples	147
Example 36 – 4-Bit ALU	147
Problems	149
<b>7. Sequential Logic</b>	<b>151</b>
7.1 Latches and Flip-Flops	151
SR Latch	151
Clocked SR Latch	153
D Latch	153
Edge-Triggered D Flip-Flop	154
Verilog Examples	156
Example 37 – Edge-Triggered D Flip-Flop	156
Example 38 – Edge-Triggered D Flip-Flop with Set and Clear	157

Example 39 – D Flip-Flops in Verilog	158
Example 40 – D Flip-Flop with Asynchronous Set and Clear	159
Example 41 – Divide-by-2 Counter	160
7.2 Registers	161
Verilog Examples	163
Example 42 – 1-Bit Register	163
Example 43– 4-Bit Register	164
Example 44 – <i>N</i> -Bit Register	165
7.3 Shift Registers	166
4-Bit Ring Counter	167
Verilog Examples	167
Example 45 – Shift Registers	167
Example 46 – Ring Counter	168
Example 47 – Debounce Pushbuttons	169
Example 48 – Clock Pulse	171
7.4 Counters	173
Arbitrary Waveform	174
Verilog Examples	175
Example 49 – 3-Bit Counter	175
Example 50 – Modulo-5 Counter	177
Example 51 – <i>N</i> -Bit Counter	178
Example 52 – Clock Divider: Modulo-10K Counter	180
Example 53 – Arbitrary Waveform	184
7.5 Pulse-Width Modulation (PWM)	185
Controlling the Speed of a DC Motor using PWM	186
Controlling the Position of a Servo using PWM	187
Verilog Examples	188
Example 54 – Pulse-Width Modulation (PWM)	188
Example 55 – PWM Signal for Controlling Servos	190
7.6 BASYS/Nexys-2 Board Examples	191
Verilog Examples	191
Example 56 – Loading Switch Data into a Register	191
Example 57 – Shifting Data into a Shift Register	193
Example 58 – Scrolling the 7-Segment Display	195
Example 59 – Fibonacci Sequence	200
Problems	203
<b>8. State Machines</b>	<b>206</b>
8.1 Mealy and Moore State Machines	206
8.2 A Moore Machine Sequence Detector	207
8.3 Mealy Machine Sequence Detector	209
Verilog Examples	210
Example 60 – Sequence Detector	210
Example 61 – Door Lock Code	215
Example 62 – Traffic Lights	219
Problems	224

<b>9. Datapaths and Control Units</b>	225
9.1 Verilog <i>while</i> Statement	225
Example 63 – GCD Algorithm – Part 1	225
9.2 Datapaths and Control Units	227
Example 64 – GCD Algorithm – Part 2	229
Example 65 – An Integer Square Root Algorithm	237
<b>10. Integrating the Datapath and Control Unit</b>	247
Example 66 –GCD Algorithm – Part 3	249
Example 67 – Integer Square Root– Part 2	253
<b>11. Memory</b>	257
Example 68 – A Verilog ROM	257
Example 69 – Distributed RAM/ROM	262
Example 70 – Block RAM/ROM	267
<b>12. VGA Controller</b>	271
Example 71 – VGA-Stripes	275
Example 72 – VGA-PROM	281
Example 73 – Sprites in Block ROM	286
Example 74 – Screen Saver	292
<b>13. PS/2 Port</b>	297
Example 75 – Keyboard	300
Example 76 – Mouse	303
<b>Appendix A – Aldec Active-HDL Tutorial</b>	313
Part 1: Project Setup	313
Part 2: Design Entry	317
Part 3: Simulation	320
Part 4: Creating a Top-level Design	324
Part 5: Synthesis and Implementation	326
Part 6: Program FPGA Board	330
<b>Appendix B – Number Systems</b>	331
B.1 Counting in Binary and Hexadecimal	331
B.2 Positional Notation	335
B.3 Fractional Numbers	336
B.4 Number System Conversions	336
B.5 Negative Numbers	340
<b>Appendix C – Making a Turnkey System</b>	344
<b>Appendix D – Verilog Quick Reference Guide</b>	346