## CONTENTS

**PREFACE**

**CHAPTER 1  INTRODUCTION**

1.1 Introduction

1.1.1 Popularity of Verilog HDL
1.1.2 Simple Examples of Verilog HDL
1.1.3 HDL-Based Design

1.2 Introduction to Verilog

1.2.1 Module Concept
1.2.2 Lexical Conventions
1.2.3 Value Set
1.2.4 Constants
1.2.5 Data Types
1.2.6 Primitives
1.2.7 Attributes

1.3 Module Modeling Styles

1.3.1 Modules
1.3.2 Structural Modeling
1.3.3 Dataflow Modeling
1.3.4 Behavioral Modeling
1.3.5 Mixed-Style Modeling

1.4 Simulation

1.4.1 Basic Simulation Constructs
1.4.2 Related Compiler Directive and System Tasks
1.4.3 A Tutorial Example

Summary

References

Problems

**CHAPTER 2  STRUCTURAL MODELING**

2.1 Gate-Level Modeling

2.1.1 Gate Primitives
### CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1.2 Tristate Buffers</td>
<td>39</td>
</tr>
<tr>
<td>2.1.3 Wired Logic</td>
<td>41</td>
</tr>
<tr>
<td>2.2 Gate Delays</td>
<td>44</td>
</tr>
<tr>
<td>2.2.1 Delay Models</td>
<td>44</td>
</tr>
<tr>
<td>2.2.2 Delay Specifications</td>
<td>46</td>
</tr>
<tr>
<td>2.3 Hazards</td>
<td>47</td>
</tr>
<tr>
<td>2.3.1 Static Hazards</td>
<td>48</td>
</tr>
<tr>
<td>2.3.2 Dynamic Hazards</td>
<td>50</td>
</tr>
<tr>
<td>2.4 Switch-Level Modeling</td>
<td>52</td>
</tr>
<tr>
<td>2.4.1 MOS Switches</td>
<td>52</td>
</tr>
<tr>
<td>2.4.2 CMOS Switch</td>
<td>56</td>
</tr>
<tr>
<td>2.4.3 Bidirectional Switches</td>
<td>58</td>
</tr>
<tr>
<td>2.4.4 Delay Specifications</td>
<td>59</td>
</tr>
<tr>
<td>2.4.5 Signal Strength</td>
<td>60</td>
</tr>
<tr>
<td>2.4.6 <em>trireg</em> Net</td>
<td>62</td>
</tr>
<tr>
<td>Summary</td>
<td>65</td>
</tr>
<tr>
<td>References</td>
<td>66</td>
</tr>
<tr>
<td>Problems</td>
<td>66</td>
</tr>
</tbody>
</table>

### CHAPTER 3  DATAFLOW MODELING

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1 Dataflow Modeling</td>
<td>69</td>
</tr>
<tr>
<td>3.1.1 Continuous Assignment</td>
<td>69</td>
</tr>
<tr>
<td>3.1.2 Expressions</td>
<td>70</td>
</tr>
<tr>
<td>3.1.3 Delays</td>
<td>72</td>
</tr>
<tr>
<td>3.2 Operands</td>
<td>74</td>
</tr>
<tr>
<td>3.2.1 Constants</td>
<td>74</td>
</tr>
<tr>
<td>3.2.2 Data Types</td>
<td>78</td>
</tr>
<tr>
<td>3.2.3 Bit-Select and Part-Select</td>
<td>80</td>
</tr>
<tr>
<td>3.2.4 Array and Memory Elements</td>
<td>82</td>
</tr>
<tr>
<td>3.3 Operators</td>
<td>84</td>
</tr>
<tr>
<td>3.3.1 Bit-wise Operators</td>
<td>84</td>
</tr>
<tr>
<td>3.3.2 Arithmetic Operators</td>
<td>86</td>
</tr>
<tr>
<td>3.3.3 Concatenation and Replication Operators</td>
<td>89</td>
</tr>
<tr>
<td>3.3.4 Reduction Operators</td>
<td>91</td>
</tr>
<tr>
<td>3.3.5 Logical Operators</td>
<td>93</td>
</tr>
<tr>
<td>3.3.6 Relational Operators</td>
<td>93</td>
</tr>
<tr>
<td>3.3.7 Equality Operators</td>
<td>94</td>
</tr>
</tbody>
</table>
CHAPTER 7  ADVANCED MODELING TECHNIQUES

7.1 Sequential and Parallel Blocks
   7.1.1 Sequential Blocks
   7.1.2 Parallel Blocks
   7.1.3 Special Features of Blocks
   7.1.4 The disable Statement

7.2 Procedural Continuous Assignments
   7.2.1 assign and deassign Statements
   7.2.2 force and release Statements

7.3 Delay Models and Timing Checks
   7.3.1 Delay Models
   7.3.2 Specify Blocks
   7.3.3 Timing Checks

7.4 Compiler Directives
   7.4.1 `define and `undef Compiler Directives
   7.4.2 `include Compiler Directive
   7.4.3 `ifdef, `else, `elsif, `endif and `ifndef Compiler Directives
   7.4.4 `timescale Compiler Directive
   7.4.5 Miscellaneous Compiler Directives

Summary
References
Problems

CHAPTER 8  COMBINATIONAL LOGIC MODULES

8.1 Decoders
   8.1.1 Decoders
   8.1.2 Expansion of Decoders

8.2 Encoders
   8.2.1 Encoders
   8.2.2 Priority Encoders

8.3 Multiplexers
   8.3.1 Multiplexers
   8.3.2 Expansion of Multiplexers

8.4 Demultiplexers
   8.4.1 Demultiplexers
   8.4.2 Expansion of Demultiplexers
8.5 Magnitude Comparators 293
  8.5.1 Magnitude Comparators 294
  8.5.2 Cascadable Magnitude Comparators 294
8.6 A Case Study: Seven-Segment LED Display 296
  8.6.1 Seven-Segment LED Display 296
  8.6.2 Multiplexing-Driven Seven-Segment LED Display 299
Summary 303
References 304
Problems 304

CHAPTER 9 SEQUENTIAL LOGIC MODULES 307
9.1 Flip-Flops 307
  9.1.1 Flip-Flops 308
  9.1.2 Metastable State 312
  9.1.3 Synchronizers 314
  9.1.4 A Switch-Debouncing Circuit 319
9.2 Memory Elements 321
  9.2.1 Registers 321
  9.2.2 Register Files 323
  9.2.3 Synchronous RAM 324
  9.2.4 Asynchronous RAM 325
9.3 Shift Registers 332
  9.3.1 Shift Registers 332
  9.3.2 Universal Shift Registers 334
9.4 Counters 338
  9.4.1 Ripple Counters 338
  9.4.2 Synchronous Counters 340
9.5 Sequence Generators 345
  9.5.1 PR-Sequence Generators 345
  9.5.2 CRC Generator/Detectors 349
  9.5.3 Ring Counters 353
  9.5.4 Johnson Counters 354
9.6 Timing Generators 356
  9.6.1 Multiphase Clock Generators 356
  9.6.2 Digital Monostable Circuits 358
Summary 360
References 361
Problems 362
CHAPTER 10  DESIGN OPTIONS OF DIGITAL SYSTEMS 367

10.1 Design Options of Digital Systems 368
  10.1.1 Hierarchical System Design 368
  10.1.2 Design Options of Digital Systems 370
  10.1.3 ASIC Designs 373
  10.1.4 Design with Field-Programmable Devices 378

10.2 PLD Modeling 382
  10.2.1 ROM 383
  10.2.2 PLA 385
  10.2.3 PAL 387
  10.2.4 PLA Modeling 391

10.3 CPLD 396
  10.3.1 XC9500 Family 397
  10.3.2 MAX7000 Family 401

10.4 FPGA 406
  10.4.1 Xilinx FPGA Devices 406
  10.4.2 Altera FPGA Devices 413

10.5 Practical Issues 418
  10.5.1 I/O Standards 419
  10.5.2 Voltage Tolerance 420

Summary 422
References 423
Problems 424

CHAPTER 11  SYSTEM DESIGN METHODOLOGY 427

11.1 Finite-State Machine 427
  11.1.1 Types of Sequential Circuits 428
  11.1.2 FSM Modeling Styles 429
  11.1.3 Implicit versus Explicit FSM 435

11.2 RTL Design 438
  11.2.1 ASM Chart 438
  11.2.2 ASM Modeling Styles 441
  11.2.3 Datapath and Controller Design 449

11.3 RTL Implementation Options 464
  11.3.1 Single-Cycle Structure 464
  11.3.2 Multiple-Cycle Structure 465
  11.3.3 Pipeline Structure 466
  11.3.4 FSM versus Iterative Logic 469
11.4 A Case Study: Liquid-Crystal Displays

11.4.1 Principles of LCDs

11.4.2 Commercial Dot-Matrix LCD Modules

11.4.3 Datapath Design

11.4.4 Controller Design

Summary

References

Problems

CHAPTER 12 SYNTHESIS

12.1 Design Flow of ASICs and FPGA-Based Systems

12.1.1 The General Design Flow

12.1.2 Timing-Driven Placement

12.2 Design Environment and Constraints

12.2.1 Design Environment

12.2.2 Design Constraints

12.2.3 Optimization

12.3 Logic Synthesis

12.3.1 Architecture of Logic Synthesizers

12.3.2 Two-Level Logic Synthesis

12.3.3 Multilevel Logic Synthesis

12.3.4 Technology-Dependent Synthesis

12.4 Language Structure Synthesis

12.4.1 Synthesis of Assignment Statements

12.4.2 Synthesis of Selection Statements

12.4.3 Delay Values

12.4.4 Synthesis of Positive and Negative Signals

12.4.5 Synthesis of Loop Statements

12.4.6 Memory and Register Files

12.5 Coding Guidelines

12.5.1 Guidelines for Clocks

12.5.2 Guidelines for Resets

12.5.3 Partitioning for Synthesis

Summary

References

Problems
CHAPTER 13  VERIFICATION

13.1 Functional Verification
   13.1.1 Design Models
   13.1.2 Simulation-Based Verification
   13.1.3 Formal Verification

13.2 Simulation
   13.2.1 Types of Simulations and Simulators
   13.2.2 Architecture of HDL Simulators
   13.2.3 Event-Driven Simulation
   13.2.4 Cycle-Based Simulation

13.3 Test Bench Design
   13.3.1 Test Bench Design
   13.3.2 Clock Signal Generation
   13.3.3 Reset Signal Generation
   13.3.4 Verification Coverage

13.4 Dynamic Timing Analysis
   13.4.1 Basic Concepts of Timing Analysis
   13.4.2 SDF and SDF Generation
   13.4.3 Delay Back-Annotation
   13.4.4 SDF Format

13.5 Static Timing Analysis
   13.5.1 Fundamentals of Static Timing Analysis
   13.5.2 Timing Specifications
   13.5.3 Timing Exceptions

13.6 Value Change Dump (VCD) Files
   13.6.1 Four-State VCD Files
   13.6.2 VCD File Format
   13.6.3 Extended VCD Files

13.7 A Case Study: FPGA-Based Design and Verification Flow
   13.7.1 ISE Design Flow
   13.7.2 Dynamic Timing Simulations
   13.7.3 An RTL-Based Verification Flow

Summary
References
Problems
<table>
<thead>
<tr>
<th>Chapter 14: Arithmetic Modules</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.1 Addition and Subtraction</td>
</tr>
<tr>
<td>14.1.1 Carry-Look-Ahead Adder</td>
</tr>
<tr>
<td>14.1.2 Parallel-Prefix Adder</td>
</tr>
<tr>
<td>14.2 Multiplication</td>
</tr>
<tr>
<td>14.2.1 Unsigned Multiplication</td>
</tr>
<tr>
<td>14.2.2 Signed Multiplication</td>
</tr>
<tr>
<td>14.3 Division</td>
</tr>
<tr>
<td>14.3.1 Restoring Division Algorithm</td>
</tr>
<tr>
<td>14.3.2 Nonrestoring Division Algorithm</td>
</tr>
<tr>
<td>14.3.3 Nonrestoring Array Divider</td>
</tr>
<tr>
<td>14.4 Arithmetic and Logic Unit</td>
</tr>
<tr>
<td>14.4.1 Shift Operations</td>
</tr>
<tr>
<td>14.4.2 ALUs</td>
</tr>
<tr>
<td>14.5 Digital-Signal Processing Modules</td>
</tr>
<tr>
<td>14.5.1 Finite-Impulse Response Filters</td>
</tr>
<tr>
<td>14.5.2 Infinite-Impulse Response Filters</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Chapter 15: Design Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.1 Bus</td>
</tr>
<tr>
<td>15.1.1 Bus Structures</td>
</tr>
<tr>
<td>15.1.2 Bus Arbitration</td>
</tr>
<tr>
<td>15.2 Data Transfer</td>
</tr>
<tr>
<td>15.2.1 Synchronous Data Transfer</td>
</tr>
<tr>
<td>15.2.2 Asynchronous Data Transfer</td>
</tr>
<tr>
<td>15.3 General-Purpose Input and Output</td>
</tr>
<tr>
<td>15.3.1 Basic Principles</td>
</tr>
<tr>
<td>15.3.2 A Design Example</td>
</tr>
<tr>
<td>15.4 Timers</td>
</tr>
<tr>
<td>15.4.1 Basic Timer Operations</td>
</tr>
<tr>
<td>15.4.2 Advanced Timer Operations</td>
</tr>
<tr>
<td>15.5 Universal Asynchronous Receiver and Transmitter</td>
</tr>
<tr>
<td>15.5.1 UART</td>
</tr>
<tr>
<td>15.5.2 Transmitter</td>
</tr>
</tbody>
</table>
A.2 Source Syntax
  A.2.1 Library Source Text 764
  A.2.2 Configuration Source Text 765
  A.2.3 Module and Primitive Source Text 765
  A.2.4 Module Parameters and Ports 765
  A.2.5 Module Items 766

A.3 Declarations
  A.3.1 Declaration Types 767
  A.3.2 Declaration Data Types 768
  A.3.3 Declaration Lists 769
  A.3.4 Declaration Assignments 769
  A.3.5 Declaration Ranges 770
  A.3.6 Function Declarations 770
  A.3.7 Task Declarations 770
  A.3.8 Block Item Declarations 771

A.4 Primitive Instances
  A.4.1 Primitive Instantiation and Instances 771
  A.4.2 Primitive Strengths 772
  A.4.3 Primitive Terminals 772
  A.4.4 Primitive Gate and Switch Types 773

A.5 Module and Generated Instantiation
  A.5.1 Module Instantiation 773
  A.5.2 Generated Instantiation 773

A.6 UDP Declaration and Instantiation
  A.6.1 UDP Declaration 774
  A.6.2 UDP Ports 774
  A.6.3 UDP Body 774
  A.6.4 UDP Instantiation 775

A.7 Behavioral Statements
  A.7.1 Continuous Assignment Statements 775
  A.7.2 Procedural Blocks and Assignments 775
  A.7.3 Parallel and Sequential Blocks 776
  A.7.4 Statements 776
  A.7.5 Timing Control Statements 777
  A.7.6 Conditional Statements 777
  A.7.7 Case Statements 778
  A.7.8 Looping Statements 778
A.7.9 Task Enable Statements 778
A.8 Specify Section 779
  A.8.1 Specify Block Declaration 779
  A.8.2 Specify Path Declarations 779
  A.8.3 Specify Block Terminals 779
  A.8.4 Specify Path Delays 780
  A.8.5 System Timing Checks 781
A.9 Expressions 783
  A.9.1 Concatenations 783
  A.9.2 Function Calls 784
  A.9.3 Expressions 784
  A.9.4 Primaries 785
  A.9.5 Expression Left-Side Values 786
  A.9.6 Operators 786
  A.9.7 Numbers 787
  A.9.8 Strings 788
A.10 General 788
  A.10.1 Attributes 788
  A.10.2 Comments 788
  A.10.3 Identifiers 788
  A.10.4 Identifier Branches 789
  A.10.5 White Space 789

INDEX 791