

Table of Contents

Preface

| | | |
|-----|--------------------------|----|
| 1.0 | Summary of the book..... | i |
| 2.0 | Acknowledgements..... | ii |

Chapter 1:Trusting Logic

| | | |
|-------|---|----|
| 1.1 | Mathematicianless enlivenment of Logic expression | 1 |
| 1.2 | Emulating the mathematician | 2 |
| 1.3 | Supplementing the expressivity of Boolean logic | 2 |
| 1.3.1 | The expressional insufficiency of Boolean logic..... | 2 |
| 1.3.2 | Supplementing the logical expression | 3 |
| 1.3.3 | Coordinating combinational expressions..... | 3 |
| 1.3.4 | The complexity burden of the time interval..... | 3 |
| 1.3.5 | Forms of supplementation other than the time interval | 4 |
| 1.3.6 | The complexity burden of asynchronous design | 5 |
| 1.3.7 | The cost of supplementation | 5 |
| 1.4 | Defining a sufficiently expressive logic | 5 |
| 1.4.1 | Logically expressing data presentation boundaries | 5 |
| 1.4.2 | Logically recognizing data presentation boundaries..... | 6 |
| 1.4.3 | Logically coordinating the flow of data..... | 8 |
| 1.4.4 | Mathematicianless completeness of expression..... | 9 |
| 1.5 | The logically determined system | 9 |
| 1.6 | Trusting the logic | 9 |
| 1.6.1 | A methodology of logical confidence..... | 9 |
| 1.7 | Summary | 9 |
| 1.8 | Exercises | 10 |

Chapter 2:A Sufficiently Expressive Logic

| | | |
|-------|---|----|
| 2.1 | Searching for a new logic | 11 |
| 2.1.1 | Expressing discrete data presentation boundaries..... | 11 |
| 2.1.2 | Logically recognizing discrete data presentation boundaries | 11 |
| 2.1.3 | The universality of the NULL function..... | 12 |
| 2.1.4 | Bounding the behavior of a combinational expression..... | 12 |
| 2.1.5 | Relationship of 4NCL to Boolean logic..... | 14 |
| 2.2 | Deriving a 3 value logic..... | 14 |
| 2.2.1 | Expressing 3NCL state holding behavior | 15 |
| 2.2.2 | 3NCL summary..... | 16 |
| 2.3 | Deriving a 2 value logic..... | 16 |

| | | |
|-------|---|----|
| 2.3.1 | The data differentiation convention | 17 |
| 2.3.2 | 2NCL as a threshold logic..... | 18 |
| 2.3.3 | 2NCL in relation to Boolean logic..... | 19 |
| 2.3.4 | Sub-variable expressivity..... | 20 |
| 2.3.5 | Completeness at the variable level..... | 20 |
| 2.3.6 | The 2NCL Orphan Path | 20 |
| 2.3.7 | 2NCL summary..... | 23 |
| 2.4 | Compromising logical completeness | 24 |
| 2.4.1 | Moving logically determined completeness boundaries farther apart | 24 |
| 2.4.2 | No logically determined boundaries in data path. | 26 |
| 2.4.3 | No logically determined boundaries at all. | 26 |
| 2.5 | Summary | 27 |

Chapter 3:The Structure of Logically Determined Systems

| | | |
|-------|---|----|
| 3.1 | The Cycle | 29 |
| 3.1.1 | The ring oscillator..... | 29 |
| 3.1.2 | Oscillator composition with shared completeness path..... | 29 |
| 3.1.3 | Cycles and 2NCL data paths..... | 32 |
| 3.1.4 | Data path abstraction..... | 33 |
| 3.1.5 | Composition in terms of cycles..... | 34 |
| 3.1.6 | Composition in terms of registration stages..... | 34 |
| 3.2 | Basic pipeline structures. | 34 |
| 3.2.1 | Pipeline fan-out..... | 35 |
| 3.2.2 | Pipeline fan-in..... | 35 |
| 3.2.3 | The pipeline ring..... | 36 |
| 3.2.4 | Cycle structure example..... | 36 |
| 3.3 | Control variables and wavefront steering | 38 |
| 3.3.1 | Steering control variables | 38 |
| 3.3.2 | Fan-out wavefront steering..... | 38 |
| 3.3.3 | Fan-in wavefront steering | 42 |
| 3.3.4 | Wavefront steering philosophy | 46 |
| 3.3.5 | Concurrent pipelined function paths..... | 48 |
| 3.4 | The logically determined system | 48 |
| 3.4.1 | A simple example system..... | 49 |
| 3.5 | Initialization | 52 |
| 3.5.1 | Initializing data wavefronts..... | 54 |
| 3.6 | Testing..... | 55 |
| 3.7 | Summary | 55 |
| 3.8 | Exercises | 56 |

Chapter 4:2NCL Combinational Expression

| | | |
|--------|--|----|
| 4.1 | Function Classification | 57 |
| 4.1.1 | Threshold function classification..... | 58 |
| 4.1.2 | Boolean function classification..... | 59 |
| 4.1.3 | Linear separability and unateness | 61 |
| 4.2 | The library of 2NCL operators..... | 61 |
| 4.3 | 2NCL combinational expression..... | 62 |
| 4.3.1 | The two roles of Boolean equations..... | 63 |
| 4.3.2 | Combinational synthesis | 63 |
| 4.4 | Example 1: Binary plus trinary to quaternary adder..... | 64 |
| 4.5 | Example 2: Logic unit..... | 65 |
| 4.6 | Example 3: Minterm construction | 68 |
| 4.7 | Example 4: A binary clipper | 70 |
| 4.7.1 | The clipper control function..... | 70 |
| 4.7.2 | The danger of minimizing the Boolean output equations..... | 72 |
| 4.7.3 | The clipper data function | 74 |
| 4.8 | example 5: A code detector | 75 |
| 4.9 | Completeness sufficiency..... | 77 |
| 4.10 | Greater combinational composition..... | 78 |
| 4.10.1 | Composition of combinational expressions..... | 78 |
| 4.10.2 | The 2NCL ripple carry adder..... | 78 |
| 4.11 | Directly mapping Boolean combinational expressions..... | 80 |
| 4.11.1 | Mapping 2 variable Boolean functions | 80 |
| 4.11.2 | The Boolean NPN classes and 2NCL expressions..... | 81 |
| 4.11.3 | Mapping NPN classes for three variable Boolean functions | 82 |
| 4.12 | Summary | 84 |
| 4.13 | Exercises | 85 |

Chapter 5:Cycle Granularity

| | | |
|-------|---|----|
| 5.1 | Partitioning combinational expressions. | 87 |
| 5.1.1 | Pipeline partitioning the combinational expression..... | 88 |
| 5.1.2 | Variable partitioning the combinational expression..... | 91 |
| 5.2 | Partitioning the data path | 91 |
| 5.3 | Two dimensional Pipelining | 92 |
| 5.3.1 | Orthogonal pipelining across a data path..... | 92 |
| 5.4 | 2D wavefront behavior | 94 |
| 5.4.1 | Orthogonal pipelining direction..... | 95 |
| 5.4.2 | Wavefront conflicts | 96 |
| 5.4.3 | Managing wavefront flow..... | 96 |
| 5.4.4 | Wavefront slope buffering | 97 |

| | | |
|-------|--|-----|
| 5.4.5 | Function structuring | 98 |
| 5.5 | 2D pipelined operations | 98 |
| 5.5.1 | 2D pipelined data path operations..... | 98 |
| 5.5.2 | 2D pipelined control operations..... | 99 |
| 5.6 | Summary | 102 |
| 5.7 | Exercises | 102 |

Chapter 6:Memory Elements

| | | |
|-------|--|-----|
| 6.1 | The ring register | 105 |
| 6.2 | Complex function registers | 108 |
| 6.2.1 | A program counter register | 108 |
| 6.2.2 | A counter register..... | 110 |
| 6.3 | The consume-produce register structure | 111 |
| 6.3.1 | The Read cycle..... | 113 |
| 6.3.2 | The Write cycle | 114 |
| 6.4 | The register file | 116 |
| 6.4.1 | A concurrent access register file | 117 |
| 6.4.2 | 2D pipelined register file | 118 |
| 6.5 | Delay pipeline memory | 118 |
| 6.6 | Delay tower..... | 118 |
| 6.7 | FIFO tower..... | 119 |
| 6.8 | Stack tower..... | 120 |
| 6.9 | Wrapper for standard memory modules..... | 120 |
| 6.9.1 | The Write operation | 121 |
| 6.9.2 | The Read operation | 121 |
| 6.9.3 | The binary conversions | 121 |
| 6.9.4 | 2D pipelined memories | 121 |
| 6.10 | Exercises | 122 |

Chapter 7:State Machines

| | | |
|-------|------------------------------------|-----|
| 7.1 | Basic state machine structure..... | 123 |
| 7.1.1 | State sequencer..... | 123 |
| 7.1.2 | Monkey get banana | 124 |
| 7.1.3 | Code detector | 125 |
| 7.1.4 | Stack controller | 127 |
| 7.2 | Exercises | 129 |

Chapter 8:Busses and Networks

| | | |
|-----|----------------------|-----|
| 8.1 | The serial bus | 131 |
|-----|----------------------|-----|

| | | |
|-------|--|-----|
| 8.1.1 | The crossbar | 132 |
| 8.2 | A fan-out steering tree..... | 135 |
| 8.3 | Fan-in steering trees do not work..... | 137 |
| 8.4 | Arbitrated steering structures..... | 138 |
| 8.4.1 | The MUTEX | 138 |
| 8.4.2 | The arbiter | 138 |
| 8.4.3 | An arbitrated 2 to 1 fan-in..... | 139 |
| 8.4.4 | Arbiter simulation | 141 |
| 8.4.5 | Arbiter timing issues | 145 |
| 8.5 | Concurrent cross bar network | 145 |
| 8.5.1 | 2D pipelining arbitrated control variables | 147 |
| 8.6 | Exercices | 147 |

Chapter 9:Multi-value Numeric Design

| | | |
|-------|--|-----|
| 9.1 | Numeric representation | 149 |
| 9.1.1 | Resource cost of transmission..... | 149 |
| 9.1.2 | Energy cost of transmission..... | 150 |
| 9.1.3 | Combined transmission costs..... | 151 |
| 9.1.4 | Resource cost of combination..... | 151 |
| 9.1.5 | Energy cost of combination | 152 |
| 9.1.6 | Combined cost for numeric combination..... | 153 |
| 9.1.7 | Summary of multi-path numeric representation | 153 |
| 9.2 | A Quaternary ALU..... | 153 |
| 9.2.1 | Quaternary logic operators..... | 154 |
| 9.3 | A Binary ALU | 160 |
| 9.4 | Comparison | 161 |
| 9.5 | Summary | 162 |
| 9.6 | Exercises | 162 |

Chapter 10:The Shadow Model of Pipeline Behavior

| | | |
|--------|---|-----|
| 10.1 | Pipeline structure | 163 |
| 10.1.1 | The cycle path and the cycle period..... | 163 |
| 10.1.2 | The wavefront path: forward latency | 164 |
| 10.1.3 | The bubble path: reverse latency: | 164 |
| 10.2 | The pipeline simulation model..... | 164 |
| 10.3 | Delays affecting throughput..... | 166 |
| 10.4 | The shadow model | 170 |
| 10.4.1 | Shadowed equal delays | 172 |
| 10.4.2 | Unshadowed delays | 174 |

| | | |
|--------|-------------------------------------|-----|
| 10.4.3 | Shadow intersection | 176 |
| 10.4.4 | A more complex example | 179 |
| 10.5 | The value of the shadow model | 180 |
| 10.5.1 | The consistently slow cycle | 181 |
| 10.5.2 | The occasional slow cycle | 181 |
| 10.6 | Exercises | 182 |

Chapter 11:Pipeline Buffering

| | | |
|--------|---|-----|
| 11.1 | Enhancing throughput..... | 183 |
| 11.1.1 | Buffer structuring for throughput..... | 185 |
| 11.1.2 | Correlated variable cycle behavior | 186 |
| 11.1.3 | Summary of throughput buffering | 187 |
| 11.2 | Buffering for constant rate throughput | 188 |
| 11.2.1 | The buffering behavior | 189 |
| 11.2.2 | The competition | 192 |
| 11.2.3 | The battle of intersecting shadows..... | 193 |
| 11.2.4 | The standoff | 194 |
| 11.2.5 | Summary of buffering for constant rate throughput | 195 |
| 11.3 | Summary of buffering..... | 195 |
| 11.4 | Exercises | 195 |

Chapter 12:Ring Behavior

| | | |
|---------|--|-----|
| 12.1 | The pipeline ring | 197 |
| 12.2 | Wavefront limited ring behavior | 199 |
| 12.2.1 | Bubble limited ring behavior | 200 |
| 12.2.2 | Delay limited ring behavior | 201 |
| 12.2.3 | Perfectly balanced ring behavior | 202 |
| 12.3 | The cycle to wavefront ratio | 203 |
| 12.4 | Ring signal behavior | 204 |
| 12.4.1 | Two wavefronts (one data wavefront) | 205 |
| 12.4.2 | Four wavefronts (two data wavefronts)..... | 205 |
| 12.4.3 | Six Wavefronts (three data wavefronts)..... | 206 |
| 12.4.4 | Eight Wavefronts (four data wavefronts)..... | 206 |
| 12.4.5 | Ten Wavefronts (five data wavefronts)..... | 207 |
| 12.4.6 | Twelve Wavefronts (six data wavefronts)..... | 207 |
| 12.4.7 | Fourteen Wavefronts (seven data wavefronts)..... | 208 |
| 12.4.8 | Sixteen Wavefronts (eight data wavefronts)..... | 208 |
| 12.4.9 | Eighteen Wavefronts (nine data wavefronts) | 209 |
| 12.4.10 | Twenty Wavefronts (ten data wavefronts) | 209 |
| 12.4.11 | Twenty two Wavefronts (eleven data wavefronts)..... | 210 |
| 12.4.12 | Twenty four Wavefronts (twelve data wavefronts)..... | 210 |

Chapter 13:Interacting Pipeline Structures

| | | |
|--------|---|-----|
| 13.1 | Preliminaries | 211 |
| 13.2 | Example 1: The basics of a two pipeline structure | 212 |
| 13.2.1 | Basics of flow | 213 |
| 13.2.2 | Increasing the throughput | 219 |
| 13.2.3 | Summary of example 1 | 224 |
| 13.3 | Example 2: A waveform delay structure..... | 224 |
| 13.3.1 | Summary of example 2 | 229 |
| 13.4 | Example 3: Reducing the period of the slowest cycle | 230 |
| 13.4.1 | Finer grained pipelining..... | 230 |
| 13.4.2 | Optimizing the logic | 232 |
| 13.5 | Exercises | 235 |

Chapter 14:Complex Pipeline Structures

| | | |
|---------|--|-----|
| 14.1 | Linear Feedback Shift Register example | 237 |
| 14.2 | Grafting pipelines..... | 238 |
| 14.2.1 | Step 1 | 238 |
| 14.2.2 | Step 2 | 240 |
| 14.2.3 | Step 3 | 243 |
| 14.2.4 | Step 4 | 245 |
| 14.2.5 | Step 5 | 246 |
| 14.2.6 | Step 6 | 248 |
| 14.2.7 | Step 7 | 249 |
| 14.2.8 | Step 8 | 251 |
| 14.2.9 | Step 9 | 252 |
| 14.2.10 | Summary | 254 |
| 14.3 | The LFSR with a slow cycle..... | 255 |
| 14.4 | Summary | 258 |
| 14.5 | Exercises | 258 |

Appendix A:Logically Determined Wavefront Flow

| | | |
|-----|---|-----|
| 1.0 | Synchronization | 259 |
| 2.0 | Wavefronts and Bubbles | 260 |
| 2.1 | Wavefront propagation..... | 261 |
| 3.0 | Extended simulation of wavefront flow..... | 263 |
| 4.0 | Wavefront and bubble behavior in a system | 266 |

Appendix B:Playing with 2NCL

| | | |
|-----|--|-----|
| 1.0 | The SR flip-flop implementations | 267 |
|-----|--|-----|

| | | |
|-----|-------------------------------------|-----|
| 1.1 | Initialization | 268 |
| 2.0 | Auto produce and auto consume | 269 |

Appendix C:Pipeline Simulation

References