

Contents

Preface	xiii
Why This Book?	xiii
Acknowledgments	xv
0 Overview	1
0.1 Introduction	1
0.2 Outline and Structure	3
0.3 On the Exercises	6
I AUTOMATA ON FINITE WORDS	
1 Automata Classes and Conversions	9
1.1 Alphabets, Letters, Words, and Languages	9
1.2 Regular Expressions: A Language to Describe Languages	10
1.3 Automata Classes	12
1.3.1 Deterministic Finite Automata	13
1.3.2 Using DFAs as Data Structures	14
1.3.3 Nondeterministic Finite Automata	19
1.3.4 Nondeterministic Finite Automata with ϵ -Transitions	20
1.3.5 Nondeterministic Finite Automata with Regular Expressions	21
1.3.6 A Normal Form for Automata	22
1.4 Conversion Algorithms	22
1.4.1 From NFA to DFA	23
1.4.2 From NFA- ϵ to NFA	27
1.4.3 From NFA-reg to NFA- ϵ	30
1.4.4 From NFA- ϵ to Regular Expressions	32
1.5 A Tour of Conversions	35
1.6 Exercises	38

2	Minimization and Reduction	49
2.1	Minimal DFAs	50
2.1.1	The Master Automaton	55
2.2	Minimizing DFAs	55
2.2.1	Computing the Language Partition	56
2.2.2	Quotienting	59
2.2.3	Hopcroft's Algorithm	61
2.3	Reducing NFAs	63
2.3.1	The Reduction Algorithm	64
2.3.2	★ Minimality Is PSPACE-Complete	68
2.4	A Characterization of Regular Languages	68
2.5	Exercises	69
3	Operations on Sets: Implementations	75
3.1	Implementation on DFAs	77
3.1.1	Membership	77
3.1.2	Complementation	77
3.1.3	Binary Boolean Operations	78
3.1.4	Emptiness	81
3.1.5	Universality	82
3.1.6	Inclusion	82
3.1.7	Equality	83
3.2	Implementation on NFAs	84
3.2.1	Membership	84
3.2.2	Complementation	85
3.2.3	Union and Intersection	86
3.2.4	Emptiness and Universality	88
3.2.5	Inclusion and Equality	91
3.2.6	★ Universality and Inclusion Are PSPACE-Complete	93
3.3	Exercises	94
4	Application I: Pattern Matching	101
4.1	The General Case	101
4.2	The Word Case	103
4.2.1	Lazy DFAs	106
4.3	Exercises	110
5	Operations on Relations: Implementations	113
5.1	Encodings	114
5.2	Transducers and Regular Relations	115

5.3	Implementing Operations on Relations	117
5.3.1	Projection	118
5.3.2	Join, Post and Pre	120
5.4	Relations of Higher Arity	124
5.5	Exercises	125
6	Finite Universes and Decision Diagrams	131
6.1	Fixed-Length Languages and the Master Automaton	132
6.2	A Data Structure for Fixed-Length Languages	133
6.3	Operations on Fixed-Length Languages	135
6.4	Determinization and Minimization	141
6.4.1	An Application: Equivalence of Digital Circuits	143
6.5	Operations on Fixed-Length Relations	145
6.6	Decision Diagrams	149
6.6.1	Decision Diagrams and Kernels	150
6.6.2	Operations on Kernels	153
6.6.3	Determinization and Minimization	157
6.7	Exercises	159
7	Application II: Verification	163
7.1	The Automata-Theoretic Approach to Verification	163
7.2	Programs as Networks of Automata	167
7.2.1	Parallel Composition of Languages	170
7.2.2	Asynchronous Product	170
7.2.3	State- and Action-Based Properties	172
7.3	Concurrent Programs	173
7.3.1	Expressing and Checking Properties	175
7.4	Coping with the State-Explosion Problem	177
7.4.1	★ Verification Is PSPACE-Complete	177
7.4.2	On-the-Fly Verification	178
7.4.3	Compositional Verification	179
7.4.4	Symbolic State-Space Exploration	183
7.5	Safety and Liveness Properties	189
7.6	Exercises	190
8	Automata and Logic	193
8.1	Predicate Logic on Words: An Informal Introduction	194
8.2	Syntax and Semantics	195
8.2.1	Syntax	195
8.2.2	Semantics	197
8.3	Macros and Examples	201
8.4	Expressive Power of $FO(\Sigma)$	203

8.5	Monadic Second-Order Logic on Words	206
8.6	Syntax and Semantics	207
8.6.1	Syntax	207
8.6.2	Semantics	207
8.7	Macros and Examples	209
8.8	All Regular Languages Are Expressible in $MSO(\Sigma)$	212
8.9	All Languages Expressible in $MSO(\Sigma)$ Are Regular	215
8.10	Exercises	225
9	Application III: Presburger Arithmetic	229
9.1	Syntax and Semantics	229
9.2	An NFA for the Solutions over the Naturals	231
9.2.1	Equations	235
9.3	An NFA for the Solutions over the Integers	236
9.3.1	Equations	240
9.3.2	Algorithms	242
9.4	Exercises	242
II	AUTOMATA ON INFINITE WORDS	
10	Classes of ω-Automata and Conversions	247
10.1	ω -Languages and ω -Regular Expressions	247
10.2	ω -Automata and the Quest for an ω -Trinity	249
10.2.1	The Quest for an ω -Trinity	250
10.2.2	Büchi Automata	251
10.2.3	Co-Büchi Automata	256
10.2.4	Rabin Automata	262
10.3	Beyond ω -Trinities	266
10.3.1	Rabin Automata, Again	267
10.3.2	Streett Automata	269
10.3.3	Parity Automata	274
10.3.4	Muller Automata	277
10.4	Summary	283
10.5	Exercises	284
11	Boolean Operations: Implementations	289
11.1	Generalized Büchi Automata	290
11.2	Union and Intersection	291
11.3	Complement	295
11.3.1	Rankings and Level Rankings	296
11.3.2	The Complement $NBA \bar{A}$	302
11.3.3	A Lower Bound on the Size of \bar{A}	306
11.4	Exercises	308

12	Emptiness Check: Implementations	313
12.1	Emptiness Algorithms Based on Depth-First Search	315
12.1.1	The Nested-DFS Algorithm	317
12.1.2	An Algorithm Based on Strongly Connected Components	323
12.2	Algorithms Based on Breadth-First Search	332
12.2.1	Emerson–Lei’s Algorithm	333
12.2.2	A Modified Emerson–Lei’s Algorithm	335
12.2.3	Comparing the Algorithms	336
12.3	Exercises	337
13	Application I: Verification and Temporal Logic	341
13.1	Automata-Based Verification of Liveness Properties	341
13.1.1	Checking Liveness Properties	342
13.1.2	Networks of Automata and Fairness	345
13.2	Linear Temporal Logic	347
13.3	From LTL Formulas to Generalized Büchi Automata	351
13.3.1	Satisfaction Sequences and Hintikka Sequences	351
13.3.2	Constructing the NGA for an LTL Formula	354
13.3.3	Size of the NGA	357
13.4	Automatic Verification of LTL Formulas	358
13.5	Exercises	361
14	Application II: MSO Logics on ω-Words and Linear Arithmetic	365
14.1	Monadic Second-Order Logic on ω -Words	365
14.1.1	Expressive Power of $MSO(\Sigma)$ on ω -Words	366
14.2	Linear Arithmetic	368
14.2.1	Encoding Real Numbers	368
14.2.2	Constructing an NGA for the Real Solutions	369
14.3	Exercises	375
	Solutions	377
	Solutions for Chapter 1	377
	Solutions for Chapter 2	403
	Solutions for Chapter 3	412
	Solutions for Chapter 4	430
	Solutions for Chapter 5	437
	Solutions for Chapter 6	445
	Solutions for Chapter 7	456
	Solutions for Chapter 8	463
	Solutions for Chapter 9	469
	Solutions for Chapter 10	478
	Solutions for Chapter 11	485

Solutions for Chapter 12	492
Solutions for Chapter 13	506
Solutions for Chapter 14	517
Bibliographic Notes	523
Bibliography	531
Index	539