Contents

Part I Introduction 1

Mathematical Background 3

0.1 Sets 3
0.2 Relations 7
0.3 Graphs 11
0.4 Proofs 15
Exercises 18

Chapter 1 Languages 25

1.1 Formalization of languages 25
1.2 Expressions and grammars 33
1.2.1 Expressions 33
1.2.2 Grammars 34
1.2.3 Specification of a programming language 39
1.3 Translations 48
Exercises 52
Programming Projects 57

Chapter 2 Automata 59

2.1 Conceptualization of automata 59
2.2 Transducers 71
2.3 Computability 78
Exercises 82
Programming Projects 88
Bibliographic notes 90

Part II Regular Languages 91

Chapter 3 Models for Regular Languages 93

3.1 Regular expressions 93
3.2 Finite automata 99
3.2.1 Basic definitions 99

3.2.2 Elimination of ε-moves 122
3.2.3 Determinism 145
3.2.4 Simplification 156
3.2.5 Minimization 171
3.3 Finite Automata and regular expressions 175
3.3.1 From regular expressions to finite automata 175
3.3.1.1 Conversion of regular expressions to finite automata 175
3.3.1.2 Scanning 196
3.3.2 From finite automata to regular expressions 209
3.3.3 Equivalence of finite automata and regular expressions 219
Exercises 220
Programming projects 227

Chapter 4 Properties of Regular Languages 229

4.1 Pumping lemma 229
4.2 Closure properties 237
4.3 Decidable problems 250
Exercises 259
Bibliographic notes 265

Part III Context-Free Languages 267

Chapter 5 Models for Context-Free Languages 269

5.1 Context-free grammars 269
5.1.1 Basic definitions 269
5.1.2 Ambiguity 299
5.1.3 Simplification 305
5.1.3.1 Elimination of useless symbols 305
5.1.3.2 Elimination of ε-productions 321
5.1.3.3 Elimination of unit productions 334
5.1.3.4 Proper context-free grammars 346
5.1.4 Normal forms 347
5.1.4.1 Chomsky normal form 348
5.1.4.2 Greibach normal form 357
5.2 Pushdown automata 381
5.2.1 Basic definitions 381
5.2.2 Extension 415
5.2.3 Determinism 432
5.3 Pushdown automata and context-free grammars 441

5.3.1 From context-free grammars to pushdown automata 442
5.3.1.1 Conversion of context-free grammars to pushdown automata 442
5.3.1.2 Parsing 477
5.3.2 From pushdown automata to context-free grammars 486
5.3.3 Equivalence of pushdown automata and context-free grammars 494
Exercises 495
Programming projects 508

Chapter 6 Properties of Context-Free Languages 511

6.1 Pumping lemma 511
6.2 Closure properties 528
6.3 Decidable problems 551
Exercises 558

Chapter 7 Special Types of Context-Free Languages and Their Models 565

7.1 Deterministic context-free languages 565
7.2 Linear and regular grammars 574
Exercises 599
Bibliographic notes 605

Part IV Beyond Context-Free Languages 607

Chapter 8 Generalized Models 609

8.1 Turing machines 609
8.1.1 Basic definitions 609
8.1.2 Determinism 631
8.1.3 Simplification 643
8.1.4 Extension 652
8.1.5 Universality 674
8.1.6 Turing machines that always halt 693
8.1.7 Linear-bounded automata 695
8.2 Two-pushdown automata 696
8.2.1 Basic definitions 696
8.2.2 Determinism 704
8.2.3 Equivalence of two-pushdown automata and Turing

machine 705
8.3 Unrestricted grammars 707
8.3.1 Basic definition 708
8.3.2 Equivalence of unrestricted grammars and Turing machines 713
8.3.3 Normal forms 722
8.3.4 Context-sensitive grammars 729
8.3.4.1 Basic definition 730
8.3.4.2 Context-sensitive grammars and linear-bounded automata 732
8.3.4.3 Context-sensitive languages and recursive languages 735
8.3.4.4 Normal forms of context-sensitive grammars 740
8.4 Hierarchy of language families 742
Exercises 743
Programming projects 753
Bibliographic notes 755

Part V Translations 757

Chapter 9 Finite and Pushdown Transducers 758

9.1 Finite transducers 758
9.2 Translation grammars and pushdown transducers 770
9.2.1 Translation grammars 770
9.2.2 Pushdown transducers 776
9.3 Compilers 787
9.3.1 Compiler structure 788
9.3.2 Scanner 789
9.3.3 Parser, semantic analyzer, and code generator 806
9.3.4 Optimizer 818
9.3.5 Execution 820
Exercises 822
Programming projects 832

Chapter 10 Turing Transducers 833

10.1 Basic definitions 833
10.2 Computability 845
10.2.1 Computers 845
10.2.2 Computable functions 851
10.2.3 Uncomputable functions 853

10.3 Decidability 856
10.3.1 Decision makers 856
10.3.2 Decidable problems 860
10.3.3 Computational complexity 861
10.3.3.1 Time complexity 862
10.3.3.2 Space complexity 866
10.3.4 Undecidable problems 867
10.3.5 Undecidability: a general approach 872
Exercises 874
Programming projects 884
Bibliographic notes 886

Bibliography 889

Indices 901

Index to Special Symbols 903

Index to Decision Problems 905

Index to Algorithms 907

Subject Index 911