Contents

Preface xiii
Acknowledgments xvii
Author xix

SECTION I INTRODUCTION

1 Mathematical Background 3
1.1 Logic 3
1.2 Sets and Sequences 4
1.3 Relations 6
1.4 Graphs 7

2 Formal Languages and Rewriting Systems 13
2.1 Formal Languages 13
2.2 Rewriting Systems 15
2.2.1 Rewriting Systems in General 16
2.2.2 Rewriting Systems as Language Models 17
2.2.3 Rewriting Systems as Computational Models 21
2.3 Synopsis of the Book 25

SECTION II REGULAR LANGUAGES AND THEIR MODELS

3 Models for Regular Languages 31
3.1 Finite Automata 31
3.1.1 Representations of Finite Automata 32
3.2 Restricted Finite Automata 34
3.2.1 Removal of ε-Rules 34
3.2.2 Determinism 38
3.2.2.1 Complete Specification 42
3.2.3 Minimization 43
3.3 Regular Expressions and Their Equivalence with Finite Automata 45
3.3.1 Regular Expressions 45
3.3.2 Equivalence with Finite Automata 47
3.3.2.1 From Finite Automata to Regular Expressions 47
3.3.2.2 From Regular Expressions to Finite Automata 49

4 Applications of Regular Expressions and Finite Automata: Lexical Analysis 61
4.1 Implementation of Finite Automata 62
4.1.1 Table-Based Implementation 62
4.1.2 Case-Statement Implementation 64
4.2 Introduction to Lexical Analysis 66
4.2.1 Lexical Units and Regular Expressions 66
4.2.2 Scanners and Finite Automata 66
4.3 Implementation of a Scanner 67

5 Properties of Regular Languages 73
5.1 Pumping Lemma for Regular Languages 73
5.1.1 Applications of the Pumping Lemma for Regular Languages 75
5.2 Closure Properties 77
5.2.1 Applications of Closure Properties 80

SECTION III CONTEXT-FREE LANGUAGES AND THEIR MODELS

6 Models for Context-Free Languages 85
6.1 Context-Free Grammars 85
6.2 Restricted Context-Free Grammars 89
6.2.1 Canonical Derivations and Derivation Trees 90
6.2.1.1 Leftmost Derivations 90
6.2.1.2 Rightmost Derivations 92
6.2.1.3 Derivation Trees 92
6.2.1.4 Ambiguity 94
6.2.2 Removal of Useless Symbols 96
6.2.3 Removal of Erasing Rules 99
6.2.4 Removal of Single Rules 103
6.2.5 Chomsky Normal Form 104
6.2.6 Elimination of Left Recursion 106
6.2.7 Greibach Normal Form 110
6.3 Pushdown Automata 113
6.3.1 Pushdown Automata and Their Languages 113
6.3.2 Equivalence with Context-Free Grammars 114
6.3.2.1 From Context-Free Grammars to Pushdown Automata 114
6.3.2.2 From Pushdown Automata to Context-Free Grammars 115
6.3.3 Equivalent Types of Acceptance 119
6.3.4 Deterministic Pushdown Automata 121

7 Applications of Models for Context-Free Languages: Syntax Analysis 131
7.1 Introduction to Syntax Analysis 132
7.1.1 Syntax Specified by Context-Free Grammars 133
7.1.2 Top-Down Parsing 134
7.1.3 Bottom-Up Parsing 136

7.2 Top-Down Parsing 141
7.2.1 Predictive Sets and LL Grammars 142
7.2.1.1 LL Grammars 145
7.2.2 Predictive Parsing 146
7.2.2.1 Predictive Recursive-Descent Parsing 146
7.2.2.2 Predictive Table-Driven Parsing 149
7.2.2.3 Handling Errors 153
7.2.2.4 Exclusion of Left Recursion 154
7.3 Bottom-Up Parsing 155
7.3.1 Operator-Precedence Parsing 155
7.3.1.1 Operator-Precedence Parser 156
7.3.1.2 Construction of Operator-Precedence Parsing Table 158
7.3.1.3 Handling Errors 159
7.3.1.4 Operator-Precedence Parsers for Other Expressions 162
7.3.2 LR Parsing 163
7.3.2.1 LR Parsing Algorithm 164
7.3.2.2 Construction of LR Table 167
7.3.2.3 Handling Errors in LR Parsing 173

8 Properties of Context-Free Languages 187
8.1 Pumping Lemma for Context-Free Languages 187
8.1.1 Applications of the Pumping Lemma 189
8.2 Closure Properties 189
8.2.1 Union, Concatenation, and Closure 190
8.2.2 Intersection and Complement 190
8.2.3 Homomorphism 192
8.2.4 Applications of the Closure Properties 192

SECTION IV TURING MACHINES AND COMPUTATION

9 Turing Machines and Their Variants 199
9.1 Turing Machines and Their Languages 199
9.2 Restricted Turing Machines 202
9.2.1 Computational Restrictions 203
9.2.2 Size Restrictions 205
9.3 Universal Turing Machines 206
9.3.1 Turing Machine Codes 206
9.3.2 Construction of Universal Turing Machines 208

10 Applications of Turing Machines: Theory of Computation 213
10.1 Computability 214
10.1.1 Integer Functions Computed by Turing Machines 214
10.1.2 Recursion Theorem 217
10.1.3 Kleene's s-m-n Theorem 219

10.2 Decidability 220
10.2.1 Turing Deciders 220
10.2.2 Decidable Problems 223
10.2.2.1 Decidable Problems for Finite Automata 223
10.2.2.2 Decidable Problems for Context-Free Grammars 225
10.2.3 Undecidable Problems 227
10.2.3.1 Diagonalization 228
10.2.3.2 Reduction 230
10.2.3.3 Undecidable Problems Not Concerning Turing Machines 233
10.2.4 General Approach to Undecidability 234
10.2.4.1 Rice's Theorem 237
10.2.5 Computational Complexity 238
10.2.5.1 Time Complexity 238
10.2.5.2 Space Complexity 240

11 Turing Machines and General Grammars 245
11.1 General Grammars and Their Equivalence with Turing Machines 245
11.1.1 General Grammars 245
11.1.2 Normal Forms 246
11.1.3 Equivalence of General Grammars and Turing Machines 248
11.1.3.1 From General Grammars to Turing Machines 248
11.1.3.2 From Turing Machines to General Grammars 249
11.2 Context-Sensitive Grammars and Linear-Bounded Automata 250
11.2.1 Context-Sensitive Grammars and Their Normal Forms 250
11.2.1.1 Normal Forms 251
11.2.2 Linear-Bounded Automata and Their Equivalence with Context-Sensitive Grammars 251
11.2.2.1 From Context-Sensitive Grammars to Linear-Bounded Automata 251
11.2.2.2 From Linear-Bounded Automata to Context-Sensitive Grammars 252
11.2.3 Context-Sensitive Languages and Decidable Languages 253
11.3 Relations between Language Families 254

SECTION V CONCLUSION

12 Concluding and Bibliographical Remarks 261
12.1 Summary 261
12.2 Modern Trends 263
12.2.1 Conditional Grammars 263
12.2.2 Regulated Grammars 263
12.2.3 Scattered Context Grammars 264
12.2.4 Grammar Systems 264
12.3 Bibliographical and Historical Remarks 264

Appendix I: Index to Special Symbols **269**
Appendix II: Index to Language Models **271**
References **273**
Bibliography **279**
Index **289**