# **CONTENTS**

LIST OF FIGURES	хi
LIST OF TABLES	xv
PREFACE	xvii
1. INTRODUCTION	1
1.1. MOTIVATION	1
1.2. SCOPE OF THE BOOK	3
1.3. CHARACTERISTICS OF NATURAL LANGUAGE 1.4. PREVIOUS WORK	5 7
2. INFORMAL DESCRIPTION OF THE ALGORITHM	9
2.1. INTRODUCTION	9
2.2. THE LR PARSING ALGORITHM	9
2.2.1. AN EXAMPLE	9
2.2.2. PROBLEM IN APPLYING TO NATURAL LANGUAGES	12 13
2.3. HANDLING MULTIPLE ENTRIES	14
2.3.1. WITH STACK LIST 2.3.2. WITH A TREE-STRUCTURED STACK	15
2.3.3. WITH A GRAPH-STRUCTURED STACK	16
2.4. AN EFFICIENT REPRESENTATION OF A PARSE FOREST	17
2.4.1. SUB-TREE SHARING	18
2.4.2. LOCAL AMBIGUITY PACKING	19
3. EXAMPLES	21
3.1. INTRODUCTION	21
3.2. THE EXAMPLE	22
3.3. MANAGING MULTI-PART-OF-SPEECH WORDS	38
3.4. MANAGING UNKNOWN WORDS	43
4. FORMAL SPECIFICATION OF THE ALGORITHM	47
4.1. INTRODUCTION	47
4.2. THE RECOGNIZER	47
4.2.1. TERMS IN GRAPH THEORY	48
4.2.2. THE GRAPH-STRUCTURED STACK	48 49
4.2.3. THE ALGORITHM FOR LR GRAMMARS	49 52
4.2.4. THE ALGORITHM FOR NON-E GRAMMARS 4.2.5. THE ALGORITHM FOR E-GRAMMARS	56
4.2.5. THE ALGORITHM FOR E-GRAMMARS 4.2.6. THE FULL VERSION OF THE ALGORITHM	60
4.2.6. THE PULL VERSION OF THE ALGORITHM  4.3. THE PARSER	64
4.3.1. ADDITIONAL TERMS IN GRAPH THEORY	64

#### viii

	4.3.2. THE PARSE FOREST 4.3.3. THE PARSING ALGORITHM 4.4. SUMMARY	64 65 69
5.	COMPARISON WITH OTHER ALGORITHMS	71
	<ul> <li>5.1. INTRODUCTION</li> <li>5.2. RECOGNITION TIME</li> <li>5.3. PARSE FOREST REPRESENTATION</li> <li>5.4. THE DEFECT OF EARLEY'S FOREST REPRESENTATION</li> <li>5.5. SUMMARY</li> </ul>	71 72 73 74 77
6.	EMPIRICAL RESULTS	79
	6.1. INTRODUCTION 6.1.1. THE PROGRAMS 6.1.2. THE SAMPLE GRAMMARS 6.1.3. THE SAMPLE SENTENCES 6.2. PARSING TIME 6.2.1. WITH RESPECT TO SENTENCE LENGTH 6.2.2. WITH RESPECT TO SENTENCE AMBIGUITY 6.2.3. WITH RESPECT TO GRAMMAR SIZE 6.3. COMPARISON WITH EARLEY'S ALGORITHMS 6.3.1. WITH RESPECT TO SENTENCE LENGTH 6.3.2. WITH RESPECT TO SENTENCE AMBIGUITY 6.3.3. WITH RESPECT TO GRAMMAR SIZE 6.4. SPACE EFFICIENCY 6.4.1. PARSE FOREST REPRESENTATION 6.4.2. GRAPH-STRUCTURED STACK 6.4.3. SIZE OF PARSING TABLES 6.5. SUMMARY	79 79 81 81 82 82 84 86 86 91 91 91 94 94
7.	LEFT-TO-RIGHT ON-LINE PARSING	95
	<ul> <li>7.1. INTRODUCTION</li> <li>7.2. RESPONSE TIME</li> <li>7.3. UNDO-ABILITY</li> <li>7.4. EARLY ERROR DETECTION</li> <li>7.5. ON-LINE PARSING AND ROBUST PARSING <ul> <li>7.5.1. LEXICAL LEVEL EXTRAGRAMMATICALITIES</li> <li>7.5.2. SENTENTIAL LEVEL EXTRAGRAMMATICALITIES</li> <li>7.5.3. DIALOG LEVEL EXTRAGRAMMATICALITIES</li> </ul> </li> <li>7.6. SUMMARY</li> </ul>	95 96 97 98 99 100 101
8.	SENTENCE DISAMBIGUATION BY ASKING	103
	8.1. INTRODUCTION 8.2. EXPLANATION LIST COMPARISON 8.2.1. THE REVISED VERSION OF ELC 8.2.2. HEAD 8.2.3. MULTIPLE EXPLANATIONS	103 104 105 106 107

8.2.4. REVISED ELC	107
8.2.5. MORE COMPLEX EXAMPLE	109
8.2.6. SIMPLE QLIST CONSTRUCTION ALGORITHM	111
8.3. DISAMBIGUATION OUT OF THE SHARED-PACKED FOREST	112
8.3.1. FOCUS	112
8.3.2. FOCUSED QLISTS	112
8.3.3. SHAVING A FOREST	114
8.4. SUMMARY	117
9. INTERACTIVE/PERSONAL MACHINE TRANSLATION	121
9.1. INTRODUCTION	121
9.2. THE DESIGN PHILOSOPHY	121
9.3. THE DESIGN DECISIONS	124
9.4. THE EXPERIMENTAL INTERACTIVE SYSTEM	124
9.5. FOUR KINDS OF AMBIGUITIES	126
9.5.1. AMBIGUITY BY MULTI-PART-OF-SPEECH WORDS	
[TYPE A]	126
9.5.2. AMBIGUITY BY CONJUNCTION [TYPE B]	127
9.5.3. AMBIGUITY BY MODIFICATION [TYPE C]	127
9.5.4. AMBIGUITY BY GENERAL AND SPECIFIC RULES	
[TYPE D]	127
9.6. EMPIRICAL RESULTS	128
9.7. DISCUSSIONS	130
9.8. SUMMARY	131
10. CONCLUDING REMARKS	133
10.1. SUMMARY OF THE BOOK	133
10.2. FUTURE WORK	134
APPENDIX A. THE PARSING TABLE CONSTRUCTOR	135
APPENDIX B. EARLEY'S ALGORITHM	139
APPENDIX C. PROOF OF CORRECTNESS OF THE ALGORITHM	141
C.1. INTRODUCTION	141
C.2. SOUNDNESS OF THE ALGORITHM	141
C.3. COMPLETENESS OF THE ALGORITHM	146
APPENDIX D. RAW EMPIRICAL DATA	151
APPENDIX E. PROGRAMS USED IN THE EXPERIMENTS	155
E.1. TOMITA'S ALGORITHM	155
E.2. EARLEY'S ALGORITHM	160
E.3. EARLEY'S ALGORITHM WITH AN IMPROVEMENT	162
E.4. LR(0) TABLE CONSTRUCTION ALGORITHM	166
E.5. UTILITY FUNCTIONS	169
APPENDIX F. GRAMMARS USED IN THE EXPERIMENTS	171

APPENDIX G. SENTENCES USED IN THE EXPERIMENTS	185
APPENDIX H. NISHIDA AND DOSHITA'S SYSTEM	191
REFERENCES	193
SUBJECT INDEX	199
<b>AUTHOR INDEX</b>	201

# List of Figures

Figure 1-1: Dense Ambiguity	U
Figure 1-2: Infinite Ambiguity	6
Figure 1-3: Cyclic Grammar	6
Figure 2-1: Example Grammar	10
Figure 2-2: LR Parsing Table	10
Figure 2-3: Trace of LR Parsing	11
Figure 2-4: Context-free Grammars and LR grammars	12
Figure 2-5: An Example Ambiguous Grammar	12
Figure 2-6: LR Parsing Table with Multiple Entries	13
Figure 2-7: Stack List	15
Figure 2-8: A Tree-structured Stack	16
Figure 2-9: A Graph-Structured Stack	17
Figure 2-10: Shared Forest	18
Figure 2-11: Unpacked Shared Forest	20
Figure 2-12: Packed Shared Forest	20
Figure 3-1: Trace of the Parser	23
Figure 3-2: Trace of the Parser (cont.)	23
Figure 3-3: Trace of the Parser (cont.)	23
Figure 3-4: Trace of the Parser (cont.)	24
Figure 3-5: Trace of the Parser (cont.)	24
Figure 3-6: Trace of the Parser (cont.)	24
Figure 3-7: Trace of the Parser (cont.)	25
Figure 3-8: Trace of the Parser (cont.)	25
Figure 3-9: Trace of the Parser (cont.)	25
Figure 3-10: Trace of the Parser (cont.)	26
Figure 3-11: Trace of the Parser (cont.)	26
Figure 3-12: Trace of the Parser (cont.)	27
Figure 3-13: Trace of the Parser (cont.)	27
Figure 3-14: Trace of the Parser (cont.)	28
Figure 3-15: Trace of the Parser (cont.)	28
Figure 3-16: Trace of the Parser (cont.)	29
Figure 3-17: Trace of the Parser (cont.)	29
Figure 3-18: Trace of the Parser (cont.)	30
Figure 3-19: Trace of the Parser (cont.)	30
Figure 3-20: Trace of the Parser (cont.)	31
Figure 3-21: Trace of the Parser (cont.)	31
Figure 3-22: Trace of the Parser (cont.)	32
Figure 3-23: Trace of the Parser (cont.)	32

## xii

Figure 3-25: Trace of the Parser (cont.)	33
Figure 3-26: Trace of the Parser (cont.)	34
Figure 3-27: Trace of the Parser (cont.)	34
Figure 3-28: Trace of the Parser (cont.)	35
Figure 3-29: Trace of the Parser (cont.)	35
Figure 3-30: Trace of the Parser (cont.)	36
Figure 3-31: Trace of the Parser (cont.)	36
Figure 3-32: Trace of the Parser (final)	37
Figure 3-33: Another Example Grammar	38
Figure 3-34: Parsing Table for figure 3-33	38
Figure 3-35: Trace of the Parser	38
Figure 3-36: Trace of the Parser (cont.)	39
Figure 3-37: Trace of the Parser (cont.)	39
Figure 3-38: Trace of the Parser (cont.)	39
Figure 3-39: Trace of the Parser (cont.)	40
Figure 3-40: Trace of the Parser (cont.)	40
Figure 3-41: Trace of the Parser (cont.)	40
Figure 3-42: Trace of the Parser (cont.)	4]
Figure 3-43: Trace of the Parser (cont.)	4]
Figure 3-44: Trace of the Parser (cont.)	4]
Figure 3-45: Trace of the Parser (final)	42
Figure 3-46: Trace of the Parser	43
Figure 3-47: Trace of the Parser (cont.)	43
Figure 3-48: Trace of the Parser (cont.)	43
Figure 3-49: Trace of the Parser (cont.)	44
Figure 3-50: Trace of the Parser (cont.)	44
Figure 3-51: Trace of the Parser (cont.)	44
Figure 3-52: Trace of the Parser (cont.)	45
Figure 3-53: Trace of the Parser (cont.)	45
Figure 3-54: Trace of the Parser (final)	45
Figure 4-1: Example of REDUCER	52
Figure 4-2: Example of SHIFTER	52
Figure 4-3: The Graph-Structured Stack	53
Figure 4-4: Example before Refinement	60
Figure 4-5: Example after Refinement	60
Figure 4-6: Another Example before Refinement	61
Figure 4-7: Another Example after Refinement	61
Figure 5-1: Heavy Ambiguity	72
Figure 5-2: Infinite Ambiguity	73
Figure 5-3: Cyclic Grammar	73
Figure 5-4: Grammar G1	74
Figure 5-5: Earley's Parse Forest	74
Figure 5-6: Underlying Parse Trees	75
Figure 5-7: Grammar G2	75
Figure 5-8: Correct Parse Trees	75
Figure 5-9: Defective Representation	76

## xiii

Figure 5-10: Wrong Parse Trees	76
Figure 6-1: Time against Sentence Length	83
Figure 6-2: Time against Sentence Length	83
Figure 6-3: Time against Ambiguity (a)	84
Figure 6-4: Time against Ambiguity (b)	85
Figure 6-5: Time against Grammar Size	85
Figure 6-6: Earley's against Tomita's	87
Figure 6-7: Farley/Tomita ratio against Sentence Length (a)	88
Figure 6-8: Farley/Tomita ratio against Sentence Length (b)	88
Figure 6-9: Earley/Tomita ratio against Sentence Ambiguity (a)	89
Figure 6-10: Earley/Tomita ratio against Sentence Ambiguity (b)	89
Figure 6-11: Earley/Tomita ratio against Sentence Ambiguity (c)	90
Figure 6-11: Earley/Tomita ratio against Sentence Ambiguity (d)	90
Figure 6-12: Earley/Tomita ratio against Grammar Size (a)	92
Figure 6-13: Earley/Tomita ratio against Grammar Size (a)	92
Figure 6-14: Earley/Tomita ratio against Grammar Size (b)	93
Figure 6-15: Size of Parse Forest against Sentence Ambiguity	93
Figure 6-16: Size of Graph-structured Stack against Sentence Ambiguity	94
Figure 6-17: Size of Grammar and Size of its Parsing Tables	96
Figure 7-1: Example of Online Parsing	97
Figure 7-2: Example of Undoing	98
Figure 7-3: Example of Earley Error Detection	100
Figure 7-4: Example of Online Spelling Correction	113
Figure 8-1: Example Grammar and Explanation Templates with a Focus	113
Figure 8-2: Parse Forest with Explanations	113
Figure 8-3: A Set of focused Qlists and pointers	
Figure 8-4: Forest before shaving off	116
Figure 8-5: Forest after shaving off node 13	117
Figure 8-6: Forest after shaving off subnode 22-1	118
Figure 8-7: Final forest after disambiguation	119

## **List of Tables**

Table 4-1:	Pre-defined functions and global variables	50
	Pre-defined functions and global variables	54
	Global variables	56
	Pre-defined functions and global variables	65
	Ambiguity of Sentence Set II	82
	Sentence Length and Number of Questions	129
	Parsing Time on Sentence Set I	152
	Parsing Time on Sentence Set II	153
	Parsing Time on Sentence Set II (cont.)	153
	Space Efficiency of Program I	154