

Statistical Methods for Speech Recognition

Frederick Jelinek

The MIT Press Cambridge, Massachusetts London, England

Preface xix

Chapter 1	
The Speech Recognition Problem 1	1.1 Introduction 1
	1.2 A Mathematical Formulation 4
	1.3 Components of a Speech Recognizer 5
	 1.3.1 Acoustic Processing 5 1.3.2 Acoustic Modeling 7 1.3.3 Language Modeling 8 1.3.4 Hypothesis Search 8 7.5.5 The Source-Channel Model of Speech Recognition 9
	1.4 About This Book 9
	1.5 Vector Quantization 10
	1.6 Additional Reading 12
	References 12
Chapter 2	
Hidden Markov Models IS	2.1 About Markov Chains 15
	2.2 The Hidden Markov Model Concept 17

2.3 The Trellis 19 2.4 Search for the Likeliest State Transition Sequence 21 2.5 Presence of Null Transitions 23 2.6 Dealing with an HMM That Has Null Transitions That Do Not Form a Loop 25 2.7 Estimation of Statistical Parameters of HMMs 27 2.8 Practical Need for Normalization 33 2.9 Alternative Definitions of HMMs 35 2.9.1 HMMs Outputting Real Numbers 35 2.9.2 HMM Outputs Attached to States 35 2.10 Additional Reading 36 References 37 3.1 Introduction 39 3.2 Phonetic Acoustic Models 40 3.3 More on Acoustic Model Training 43 3.4 The Effect of Context - 44 3.5 Viterbi Alignment 45

viu

Chapter 3

The Acoustic Model

39

		3.6 Singleton Fenonic Base Forms 45
		3.7 A Needed Generalization 47
		3.8 Generation of Synthetic Base Forms 48
		3.9 A Further Refinement 51
		3.10 Singleton Base Forms for Words Outside the Vocabulary 52
		3.11 Additional Reading 52
		References 54
Chapter 4		
Basic Language Modeling	57	4.1 Introduction 57
		4.2 Equivalence Classification of History 59
		4.3 The Trigram Language Model 60
		4.4 Optimal Linear Smoothing 62
		4.5 An Example of a Trigram Language Model 66
		4.6 Practical Aspects of Deleted Interpolation 66
		4.7 Backing-Off 69
		4.8 HMM Tagging 70

	4.9 Use of Tag Equivalence Classification in a Language Model 72
	4.10 Vocabulary Selection and Personalization from Text Databases 73
	4.11 Additional Reading 75
	References 76
Chapter 5	
The Viterbi Search 79	5.1 Introduction 79
	5.2 Finding the Most Likely Word Sequence 79
	5.3 The Beam Search 81
	5.4 Successive Language Model Refinement Search 84
	5.5 Search versus Language Model State Spaces 86
	5.6 Af-Best Search 86
	5.7 A Maximum Probability Lattice 89
	5.8 Additional Reading 90
	References 90
Chapter 6	
Hypothesis Search on a Tree and the Fast Match 93	6.1 Introduction 93
	6.2 Tree Search versus Trellis (Viterbi) Search 95

		6.3 A* Search 95
		6.4 Stack Algorithm for Speech Recognition 97
		6.5 Modifications of the Tree Search 99
		6.6 Multiple-Stack Search 99
		6.6.1 First Algorithm 100 6.6.2 A Multistack Algorithm 101 6.6.3 Actual Multistack Algorithm 102
		6.7 Fast Match 103
		6.8 The Cost of Search Shortcuts 109
		6.9 Additional Reading 110
		References 110
Chapter 7		
Elements of Information Theory	113	7.1 Introduction 113
		7.2 Functional Form of the Basic Information Measure 114
		7.3 Some Mathematical Properties of Entropy 119
		7.4 An Alternative Point of View and Notation 123
		7.5 A Source-Coding Theorem 126
		7.6 A Brief Digression 132

Contents

	7.7 Mutual Information 132
	7.8 Additional Reading 135
	References 135
Chapter 8The Complexity of Tasks—The Qualityof Language Models137	8.1 The Problem with Estimation of Recognition Task Complexity 137
	8.2 The Shannon Game 139
	8.3 Perplexity 141
	8.4 The Conditional Entropy of the System 142
	8.5 Additional Reading 144
	References 145
Chapter 9	
The Expectation-Maximization Algorithm and Its Consequences 147	9.1 Introduction 147
	9.2 The EM Theorem 147
	9.3 The Baum-Welch Algorithm 149
	9.4 Real Vector Outputs of the Acoustic Processor 152
	9.4.1 Development for Two Dimensions 152 9.4.2 The Generalization to k Dimensions 158
	9.5 Constant and Tied Parameters 158
	9.5.1 Keeping Some Parameters Constant 158

	9.5.2 Tying of Parameter Sets 159
	9.6 Tied Mixtures 161
	9.7 Additional Reading 163
	References 163
Chapter 10	
Decision Trees and Tree Language Models 165	10.1 Introduction 165
	10.2 Application of Decision Trees to Language Modeling 166
	10.3 Decision Tree Example 166
	10.4 What Questions? 168
	10.5 The Entropy GoodnessCriterion for the Selection ofQuestions, and a Stopping Rule 170
	10.6 A Restricted Set of Questions 172
	10.7 Selection of Questions by Chou's Method 173
	10.8 Selection of the Initial Split of a Set <i>Sf</i> into Complementary Subsets 176
	10.9 The Two-ing Theorem 177
	10.10 Practical Considerations of Chou's Method 179
	10.10.1 Problem ofOs in the q-Distribution: The Gini Index 179 10.10.2 Equivalence Classification Induced by Decision Trees 182

10.10.3 Computationally Feasible Specification of Decision Tree Equivalence Classes 183

10.11 Construction of Decision Trees Based on Word Encoding 184

10.12 A Hierarchical Classification of Vocabulary Words 186

10.13 More on Decision Trees Based on Word Encoding 188

10.13.1 Implementing Hierarchical Word Classification 188 10.13.2 Predicting Encoded Words One Bit at a Time 189 10.13.3 Treatment of Unseen Training Data 190 10.13.4 Problems and Advantages of Word Encoding 190

10.14 Final Remarks on the Decision Tree Method 191

10.14.1 Smoothing 191 10.14.2 Fragmentation of Data 192

10.15 Additional Reading 193

References 194

Chapter 11Phonetics from Orthography: Spelling-
to-Base Form Mappings11.1 Over
Generation

11.1 Overview of Base Form Generation from Spelling 197

11.2 Generating AlignmentData 199

11.3 Decision Tree Classification of Phonetic Environments 201

11.4 Finding the Base Forms 204

	11.5 Additional reading 204
	References 205
Chapter 12 Triphones and Allophones 207	12.1 Introduction 207
	12.1 Introduction 207
	12.2 Triphones 208
	12.3 The General Method 210
	12.4 Collecting Realizations of Particular Phones 210
	12.5 A Direct Method 211
	12.6 The Consequences 214
	12.7 Back to Triphones 215
	12.8 Additional Reading 217
	References 218
Chapter 13	
Maximum Entropy Probability Estimation and Language	13.1 Outline of the Maximum Entropy Approach 219
Models 219	13.2 The Main Idea 220
	13.3 The General Solution 221
	13.4 The Practical Problem 222
	13.5 An Example 224
	13.6 A Trigram Language Model 227
	13.7 Limiting Computation 228

13.8 Iterative Scaling 231

13.9The Problem of FindingAppropriate Constraints233

13.10 Weighting of Diverse Evidence:Voting 234

13.11 Limiting Data Fragmentation: Multiple Decision Trees 236

13.11.1 Combining DifferentKnowledge Sources 23613.11.2 Spontaneous Multiple TreeDevelopment 238

13.12 Remaining Unsolved Problems 240

13.13 Additional Reading 241

References 242

Chapter 14

Three Applications of Maximum Entropy Estimation to Language Modeling 245 14.1 About the Applications 245

14.2 Simple Language Model Adaptation to a New Domain ' 246

14.3 A More Complex Adaptation 248

14.4 A Dynamic Language Model: Triggers 251

14.5 The Cache Language Model 253

14.6 Additional Reading 255

References 255

Chapter 15 **Estimation of Probabilities from Counts** Inadequacy of Relative 15.1 and the Back-Off Method Frequency Estimates 257 257 15.2 Estimation of Probabilities from Counts Using Held-Out Data 258 15.2.1 The Basic Idea 258 15.2.2 The Estimation 259 15.2.3 Deciding the Value of M 261 15.3 Universality of the Held-Out Estimate 262 15.4 The Good-Turing Estimate 263 Applicability of the Held-Out 15.5 and Good-Turing Estimates 265 15.6 Enhancing Estimation Methods 268 15.6.1 Frequency Enhancement of Held-Out Estimation of Bigrams 268 Frequency Enhancement 15.6.2 of Good-Turing Estimation of Bigrams 269 15.6.3 Other Enhancements 270 15.7 The Back-Off Language Model 271 15.8 Additional Reading 273 References 274 Name Index 275 Subject Index 279